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SKIN FRICTION MEASUREMENT TECHNIQUES FOR SCRAMJET APPLICATIONS - PHASE I: PRELIMINARY DESIGN

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The objective of this program was to carry out a preliminary design of a gauge to measure skin friction of a scramjet combustor. Preliminary designs of two skin friction measurement approaches have been completed. The work was accomplished by The Marquardt Company and a subcontracted group from Virginia Polytechnic Institute (VPI).

With the recent interest in hypersonic flight the challenge to obtain accurate skin friction measurements has become necessary. For example, at a flight condition of Mach 8 at 100,000 feet altitude the estimated skin friction drag of a scramjet engine is approximately 36% of the net thrust. The environment within a scramjet combustor is extremely hostile to any physical object, thus increasing the difficulty of successful measurement of skin friction.

The first approach reported is the Cantilever Beam (Design A) design based on the use of a multi-purpose displacement transducer which has the property of being very sensitive while still being stiff. The second or the Thin Film (Design B) approach is a newly established concept by VPI. The design exploits thin film sputtering technology for the purpose of

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attaching microstrain gauges.

Design A prototype was successfully tested at NASA Langley Research Center's vitiated facility at conditions representative of a scramjet combustor. The results are presented and give a positive outlook for further development.

SUMMARY

Preliminary designs of two skin friction measurement approaches have been completed. The work was carried out by personnel from Engineering at Marquardt, and a subcontracted group from Virginia Polytechnic Institute (VPI). This subcontractor was chosen based on the broad background and experience of the research team in the areas of aerodynamics, heat transfer, skin friction measurement technology and strain gauge instrumentation.

The objective of the program was to investigate measurement techniques applicable to the SCRAMJET environment. With the more recent development of high speed aircraft, such as the X-15 and the X-30, the challenge to overcome skin friction measurement has become critical. For an assumed condition of Mach 8 flight at 100,000 feet, the estimated skin friction drag of the engine is 36% of the net thrust.

The technical analyses at Marquardt was carried out under a "matrix" organization. A design review and evaluation of each measurement approach was conducted by the Heat Transfer, Material Science, Aerodynamics, Structures, Test, and Design groups. The work conducted at VPI centered around the development, fabrication, calibration, and limited airflow testing of design prototypes.

The Cantilever Beam (Design A) approach is based on the use of a multi-purpose displacement transducer which has the property of being very sensitive while still being stiff. The Thin Film (Design B) approach is a newly established concept by VPI. The design exploits thin film sputtering technology for the purpose of attaching microstrain gauges.

The objectives of this Phase I - Preliminary Design have been satisfied. Preliminary proof-of-concept test results from both designs are very positive. Each approach is capable of meeting or exceeding all of the required performance specifications. Because of their different strengths and weaknesses, together they form to a measurement system applicable to a wide range of high-temperature, high-speed test applications.

FOREWORD

This investigation of skin friction measurement approaches for use in the supersonic combustion ramjet environment (SCRAMJET) was conducted by The Marquardt Company under contract F33615-87-C-2755 from Wright Research and Development Center, Aero Propulsion and Power Laboratory (WRDC/POP). The program was carried out by personnel from Engineering at Marquardt, and a subcontracted group from Virginia Polytechnic Institute (VPI).

The program was a six-month effort starting in September 1989 through to February 1990. Wallace G. Harkins served as program manager and Robert C. Steele was the principle investigator/project engineer. Drs. Thomas E. Diller, Joseph A. Schetz, and Alfred L. Wicks led the research effort at VPI. The Air Force Project Engineer was Mr. John R. Smith, WRDC/POPR.

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1.0 INTRODUCTION

The supersonic combustion ramjet (SCRAMJET) engine achieves its propulsive efficiency in the hypersonic flight speed application by adding impulse without reducing the flow through velocity to low subsonic Mach numbers. The velocity of the working fluid (air) through the engine is high and consequently the flow impedance from skin friction is a relative high proportion of the total impedance. The requirement to correlate the various contributors to the propulsive impulse from component measurements stems from the great difficulty encountered in ground testing the SCRAMJET over a full range of simulated flight conditions. The ability to measure skin friction therefore became a goal in the overall hypersonic research program.

In most applications of fluid mechanics a knowledge of the drag created by fluid flowing over a solid surface is essential to the understanding of the performance of the system. Probably the first systematic investigations were made over 100 years ago by Froude (Reference 1) who measured the drag of a series of planks towed at various speeds along a tank. The direct measurement of skin friction by force balance was an essential step in setting up the basic skin friction laws for the generally accepted estimations for incompressible flow (Reference 2). Because of the limited understanding of turbulent flows there has been the need to extend direct skin friction measurements to compressible flows, but the difficulty of applying the technique in many situations such as flows with pressure gradients has led also to the development of indirect means of obtaining skin friction (References 3 and 4).

In the 1985 time period, prior to this current program, Marquardt began to investigate the instrumentation technology for skin friction and its application to the SCRAMJET environment. A limited survey found that the Applied Physics Laboratory of Johns Hopkins University (APL-JHU) and Naval Ordnance Laboratory Naval Surface Weapons Center had achieved some success in direct skin friction measurements. Later, under the present program, it was determined that work was being done at NASA-Langley and Virginia Polytechnic Institute (VPI) in this application. As will be presented in this report, Marquardt proceeded to contact VPI and successfully established a subcontract agreement for the university personnel to provide technical expertise as it related to the current program.

The objective of the program was to carry out a preliminary design of approach(es) for the measurement of SCRAMJET skin friction. The environment within a SCRAMJET is extremely hostile to any physical object. The skin friction measurement device must therefore be restricted to the boundary which contains the flow. The energy imposed on the boundary by combustion pressures, acoustic pressure and heat (radiant or convected) will interact with the physical mechanism used to measure skin friction. Therefore, the challenge was to devise a suitable method of measuring skin friction which can withstand these interfering aspects of the environment.

Presented in this report is the survey and selection of the subcontracted research group which provided much technical expertise. Two skin friction measurement approaches are presented in detail, with some limited proof-of-concept testing included. Specifications for both designs are outlined which can be used for further design development. Conclusions and recommendations for future work are also stated.

2.0 BACKGROUND

The evaluation of flight technology through the past and into the future has one common challenge - the provision of sufficient propulsion power to overcome the aerodynamic drag of the aircraft. One primary component of this drag is the skin friction of the air over the aircraft. Study has been focused upon quantifying this friction drag for decades. With the more recent development of high-speed aircraft, such as the X-15 and X-30, wherein increased aerodynamic heating occurs, the relationship between skin friction and convection heating has became increasingly significant.

As we pursue sustained flight into the hypersonic regime, the SCRAMJET engine shows promise of providing propulsion to reach hypersonic speeds. Two major concerns prevail which might restrict the degree of success of the SCRAMJET (Reference 5). These are the internal drag of the propulsion gas as it flows through the engine and the internal heating of the engine from this same gas. Both the drag upon and the convection heating of the engine walls are strongly related to the skin friction of this gas as it shears over the internal surface of the SCRAMJET.

The SCRAMJET engine concept is being developed for hypersonic propulsion because of its impulse efficiency, simplicity, and relatively low structural loads. In order to retain impulse efficiency, it must obviously produce acceptable total thrust throughout the required hypersonic flight regime. As flight speeds increase, say through the 6 to 12 Mach number range, the net thrust of the engine becomes a smaller percent of the relatively huge values of inlet and exhaust momenta. This is due to the increasing large values of inlet and exhaust gas velocities. It follows that if internal gas velocities increase as well, the internal friction drag can also increase with flight speed. As stated earlier, the concern here is that if the internal friction drag becomes too high, relative to the net "inviscid" thrust of the engine, the delivered flight speed of a selected SCRAMJET could fall short of propulsion requirements in a given application (Figure 1).

As an example, some simple, expedient calculations were made using a "typical, contemporary" SCRAMJET configuration to exhibit the above point. Assumed conditions were 8.0 flight Mach number at 100,000 feet of altitude giving an aerodynamic q of about 100 psf. The net inviscid thrust of the configuration was 1192 lbs. The internal drag force was computed assuming about 15,000 sq. in. engine surface area, an average internal static pressure and temperature of 7 psia and 3500°R, respectively. The average internal velocity was 6000 fps, and the average friction coefficient (f/2) was assumed at 0.002. This resulted in a friction drag force of 436 lbs. This drag was about 36% of the engine net thrust.

While the above quantities are certainly not precise, they do show that the friction drag is a significant contributor. Thus, it appears important that accurate predictions of SCRAMJET friction drag can be vital to a given program. Unfortunately, the internal gas flow through a SCRAMJET combustor is unique to most of the skin friction data base. The high temperature, high velocity, vibrating and pulsating environment to which a skin friction gauge

is exposed offers a challenging task to obtain such data. It would be expedient to the thrust versus drag problem if a means of correlating internal friction drag could be found which is more simple than the skin friction gauge approach.

Marquardt test experience with ramjets and SCRAMJETS in our facility provides a stabilizing awareness of the requirements of a skin friction gauge. First, it must accommodate a heat flux of 1 to 5 Btu/sec.-sq. in. It must measure a shear force on the order of 0.01 to 0.05 lb. and indicate such in an accurate signal. It must match the heat flux of surrounding, particularly the upstream regions. The shearing gas flow will have approximately 5500 to 7500°R gas temperature, 5000 to 8000 fps velocity, and 5 to 15 p a static pressure. The gauge must resist and accommodate the vibration of the engine upon which it will be mounted and resist the pulsations of characteristic combustion pressure oscillations.

Finally, it should be pointed out that significant supplementary data acquisition will be required to provide reliable correlations. These will include wall temperature and heat flux measurements adjacent to the gauge. Aerodynamic data in the vicinity of the gauge will also be required to evaluate density, velocity and other flow conditions.

3.0 SURVEY AND SELECTION

In accordance with Air Force contract requirements a survey was carried out to review and identify the current status of skin friction measurement research. Also conducted was a "request for proposal" to research groups which expressed an interest and willingness to respond to the task of assisting in the design of a skin friction measurement device as a subcontractor to Marquardt. An exhaustive screening process resulted in 6 research groups from an original 21 which responded with proposals to Marquardt. After careful review and consideration the decision to recommend Virginia Polytechnic Institute (VPI) was made. This was based on the broad background and experience of the research team in the areas of aerodynamics, heat transfer, skin friction measurement technology and strain gauge instrumentation.

The team was made up of members from the Aerospace, Mechanical and Electrical engineering departments who each provided a different expertise (Figure 2). Dr. Schetz has broad experience in direct skin friction measurement devices of various designs. His first studies were conducted in the early 1970's (Reference 6), and have continued up to the present time. Dr. Diller has done extensive work in the measurement of heat transfer in a variety of fluid flows. Dr. Wicks has many years of experience in strain measurements at elevated temperatures and in the development of specialized instrumentation. Though not directly involved in the present Phase I program, Dr. Onishi was still able to provide his knowledge and experience in the area of sputtered micro sensors.

It became immediately apparent to Marquardt that the selection of VPI to provide technical support was indeed the correct decision. Marquardt was able to work effectively with VPI throughout the program thus providing the Air Force with the best possible nationwide effort on this critical issue.

4.0 DESIGN SELECTION

In accordance with the Air Force's Statement-Of-Work (SOW) various skin friction measurement approach(es) were to be evaluated. The pros and cons of the candidate approach(es) were to be identified. On the most likely approach(es) a preliminary design and analysis was to be carried out. Also to be determined was a design specification which would be used for a possible Phase II - Detailed Design.

Originally five different approaches from VPI were presented to Marquardt for technical review. Work progressed at Marquardt and VPI to evaluate these concepts relative to the goals and time frame of Phase I (Figure 3). Correspondingly it was decided that the design effort would focus on the Cantilever Beam (Design A) and the Thin Film (Design B) designs. The other designs considered were on a more fundamental level. The Pendulum (Design C) concept was basically a sensing head mounted on the end of a rigid beam which was suppported at mid-length on a frictionless hinge. A weight was attached to the opposite end which would provide an extremely sensitive restoring force. The Shear Cube (Design D) concept exploited the use of microstrain gauges attached along the diagonals of the cube to sense shear force induced by the airflow. No actual physical layout was developed. The last concept (Design E) reviewed was the viscous film technique which is being used in low temperature environments at other laboratories (Penn State, NASA Ames). Application in the high temperature SCRAMJET has been questioned since some oil-like fluid is required to withstand this hostile environment. This concept was also dropped after several technical discussions between Marquardt, VPI, Penn. State and NASA-AMES personnel.

Presented here are the two chosen designs. The functional operation of the devices, the critical design parameters, and the technical analyses at Marquardt and VPI are detailed.

4.1 DESIGN A - CANTILEVER BEAM

This type of skin friction measurement device has been in use at VPI for over 10 years. Up until a few years ago the device was used solely for low temperature applications. Through work with Dick Hellbaum (NASA-Langley) Dr. Schetz was able to make some preliminary modifications to the basic design which would allow for operation in high temperature environments. These preliminary modifications provided the background for the work accomplished with Marquardt.

4.1.1 Functional Operation

This design is based on the use of the Kistler-Morse Displacement Sensor (Figure 4) which, when deflected generates an output by straining two piezoresistive crystals which are internal to the sensor. As presented in Figure 5, the device is made up of several parts, namely: the Kistler-Morse sensor;

the cantilever beam which is attached to the end of the displacement sensor; the water-cooled housing in which the displacement sensor and cantilever beam are positioned; and the damping/heat transfer fluid which fills the annulus between the housing and the beam.

The cantilever beam is positioned such that its top surface is flush with the surface of the combustion chamber. During testing, the passing airflow over the top of the beam will cause a minute deflection (< 1 mil) to the end of the beam, resulting in a generated output. Using a previously determined calibration, the skin friction is known. Typically these "deflection" devices are calibrated by hanging small weights of different sizes from the end of the beam, and recording the outputs. Another calibration technique being tested by Dick Hellbaum at NASA-Langley is the use of a rotating disc to create Couette flow over the end of the beam. It has been arranged between Dr. Schetz and Mr. Hellbaum to calibrate the devices being developed at VPI in the NASA-Langley laboratory.

The annulus is filled with a fluid which has the characteristics to provide damping of the model vibrations, and create a better medium for the transfer of heat from the hot exposed surfaces to the water-cooled housing. It is necessary to cool the metal components, and maintain the piezoresistive crystals at a constant temperature.

4.1.2 Critical Design Parameters

The following are the critical design parameters which were identified.

1. Various aerodynamic issues concerning the use of a "floating element" to measure skin friction are being investigated. Such concerns like misalignment effects, gap size tolerances, pressure gradient effects, and others must be understood and addressed.

2. Temperature and heat flux issues with combustor wall temperatures as high as 1000°F must be evaluated. The matching of the heating characteristics of the measurement device to the test model is essential. Physical expansion of the various components including the fluid in the annulus will be reviewed. The requirements for the cooling system need to be identified, and the proposed system integrated into the overall design.

3. The WRDC specification to achieve a natural frequency of 1000 Hz needed to be evaluated. It was believed that this frequency will be difficult to achieve if the use of the damping fluid is considered necessary.

4. The choice of materials is very critical when working in any hot environment. The possible use of ceramics will be considered where appropriate.

5. The issue of zero drift will continue to be addressed relative to the characteristics of the Kistler-Morse piezoresistive crystals, and the accompanying electronics. It is believed that if the temperature of the crystals can be maintained at a constant value, then the output will experience relatively no drift.

4.1.3 Technical Analyses at Marquardt

Under the matrix organization at Marquardt, a design team was organized from the various technical support groups to analyze the proposed design concepts. The distribution of effort by the various groups is shown as Figure 6. The work accomplished by these support groups is now presented.

4.1.3.1 Heat Transfer

It has long been recognized that skin friction and convection heat transfer are closely related (Reference 7). Reynolds' Analogy showed us that from a molecular point of view fluid friction and heat conduction through the fluid obey the same law of motion; namely, momentum exchange. This is the basis of convection heat transfer. Well-established equations have been formulated to describe Reynolds' Analogy, but with serious limitations in their development. These include streamline flow in the boundary layer (molecular mixing and energy exchange) and a gas properties requirement that the Prandtl Number be unity. Still, the relationship between fluid friction and convection heat transfer in turbulent flow has been correlated experimentally, as well as analytically. To achieve representative skin friction measurements, it is necessary to duplicate the local heat flux or account for the difference if variations are present.

Reynolds' Analogy states that,

$$\frac{\tau_g}{\tau_w} = \frac{q_g}{q_w}$$

where,

τ_g - skin friction of gauge

τ_w - skin friction of surrounding combustor wall

q_g - heat flux of gauge

q_w - heat flux of surrounding wall

and further,

$$\frac{\tau_g}{\tau_w} = \frac{q_g}{q_w} = \frac{T_{aw} - T_g}{T_{aw} - T_w}$$

where: T_{aw} - adiabatic wall temperature of combustor

T_g - surface temperature of skin friction gauge

T_w - surface temperature of combustor

if it can be argued that,

$$T_{aw} \gg T_g \text{ and } T_{aw} \gg T_w$$

then

$$(T_{aw} - T_g) \approx (T_{aw} - T_w)$$

and finally

$$\tau_g \approx \tau_w$$

A question to be answered is how much of a difference in wall temperatures can be tolerated to maintain the required accuracy in measured skin friction. This is one of the issues that was addressed by the heat transfer group.

A transient heat transfer model of the cantilever beam head and surrounding housing was developed using a Marquardt code which is similar to SINDA. The model was based on the dimensions of a prototype gauge from VPI (Figure 14). The purpose of the analysis was to understand the thermal characteristics of the basic design. It was proposed that this analytical "tool" would be able to provide information that could be used in furthering the design of the device.

To model a realistic combustion scenario a "typical" test run was defined. For the first run an adiabatic wall temperature rise from 1500°F to 4800°F in 5 seconds was incorporated into the computer model. This "SCRAMJET" condition was held for 25 seconds and then the run was terminated. This scenario was very similar to that which a VPI prototype gauge was subject to at NASA-Langley.

The first task accomplished was to understand the differences in using a solid head mounted on a solid beam, or a solid head mounted on a hollow beam. A further beam was analyzed which had a solid section added halfway along the hollow section to act as a heat sink.

The steps followed to build a more complete model where: (1) allow radiation cooling, (2) add a fluid to the annulus, (3) simulate water cooling in the housing, (4) consider water cooling to the beam itself, (5) optimize the beam design. The model was easy to use and provided much thermal information pertaining to this design.

For a 30 second simulated test run, the temperature profiles for the three beams are presented for comparison in Figure 7. Observe from this figure that the hollow tube isolates the solid head causing a higher temperature. Another observation is that the added "heat sink" drops the tube temperature to ambient at 0.8 inches instead of 1.2 inches. These results were for conduction only along the beam.

Further development of the model was accomplished by allowing radiation and conduction across the annulus. In an attempt to cool the spool-shaped solid head, a water cooled housing was added to the model. The head was surrounded by a 0.25 inch ID water jacket, which consisted of 3 water channels of 0.10 inch X 0.10 inch square cross-section. The solid head and tube were segmented to have 56 thermal nodes. Three cases were modeled and analyzed. The first case allowed radiation cooling from the beam to the surrounding water-cooled housing. The second case added a Dow Chemical liquid (VP-1) to the annulus to aid in the cooling. The liquid was assumed not to boil for the sake of analysis. Typically, these high temperature fluids are limited to around 800°F. The third case replaced the VP-1 with a liquid metal (Gallium-Indium- Tin). See Figure 8 for comparison of these three cases.

The results are summarized in the following way:

A. At the end of the 30 second run, the top layer of the solid head reaches 1900°F when radiation cooled, and 1650°F when cooled by a liquid (in this case, VP-1). Overall, it's above 1000°F when cooled by radiation alone, and still above 700°F when cooled with the liquid. The latter implies there would be a rather vigorous boiling all over the surface of the solid head by the end of the run.

B. The bottom of the tube remains cool, very close to the initial temperature of 70°F. It was 71.3°F with radiation cooling, and 70.9°F on the second case. This means that the crystal strain gauge does not experience any significant temperature change, at least during the first 30 seconds.

C. Because of the temperature rise, the overall thermal expansion at the end of the 30-second run is estimated at 0.0122 inch (12.2 mil) when radiation cooled, and 0.0085 inch (8.5) mil) when cooled by VP-1. Thermal expansion should not be a concern if the surrounding combustor wall expands at the same rate.

D. Figure 8 shows that the use of Gallium-Indium-Tin (GIT) in the annulus can maintain the surface temperature of the head at below 500°F. This is a very significant result since water cooled combustor rigs can typically experience surface temperatures of 400 - 800°F. Matching the surface temperature of the gauge with the surrounding test rig temperature is critical for the accurate measurement of skin friction. Since skin friction is proportional to the heat flux (Reynolds' analogy), and heat flux is proportional to the difference between the adiabatic wall temperature and the actual wall temperature, then the skin friction becomes a function of the difference in the wall temperatures. A question to be answered is how much of a difference in wall temperatures can be tolerated to maintain the required accuracy. The present computer model suggests that a temperature difference between the gauge and the surrounding wall of 100°F results in only a 3% difference in skin friction.

4.1.3.2 Aerodynamics

To effectively design a "floating element" measurement device an understanding of potential aerodynamic effects must be achieved. Much research and information has been generated over the years (Reference 2, 3, 8) addressing the effects of a skin friction sensing device which is exposed to the airflow. As discussed in these references, there can exist "secondary" forces due the inherent design of the sensing device. Such details as height misalignment, gap size around the head, and the senser-head lip design can all contribute error to the results (Figure 9).

For the proposed dimensions of 0.25 inch diameter (D) and a gap (G) around the sensor-head of 4 mil (D/G = 62.5), the misalignment effects are anticipated to be minimal. It is presented by Allen (Reference 8) that the larger the gap, the more tolerant the flow is to height misalignment. Further, a ratio of D/G = 100 is considered more ideal. For smaller gaps, sensitivity due to misalignment is increased, but larger gaps may have a more noticeable effect on the flow in the region of the gauge. Of course the ideal situation is zero height misalignment, but this is not realistic. It is proposed that the gauge will function successfully with a misalignment tolerance no greater than ± 2 mil.

Additional work has been carried out at Marquardt by modeling the height misalignment problem with a 2-D finite element Computational Fluid Dynamic code. The code cannot model a turbulent boundary layer with a sudden upward or downward step. Alternately, the modeling of a laminar boundary layer was carried out to provide background to the turbulent case. We appreciate the fact that the actual SCRAMJET environment is believed to be turbulent, but decided that this effort was still worthwhile. Since doing this work the code has been updated to model turbulent flow.

The analysis was performed on a flat plate with the simulated misaligned skin friction gauge located 2.5 inch from the front edge. Two step heights of 20 and 5 mil were analyzed. A smaller height of 2 mil was desired but was

found to be impossible to model due to the limitations in the density of the mesh generation. This problem has been overcome which now allows for modeling of turbulent flow over misalignments of less than 2 mils.

Upward Configuration

To evaluate the error encountered for the upward or protruding configuration, the average pressure was determined along the front and back surfaces of the modeled gauge. The "net" force was calculated by using the difference of the front and back pressures as follows:

$$F(net) = \{ P(\text{front wall}) - P(\text{back wall}) \} \times \text{Area of wall}$$

The skin friction that would be indicated on the measuring device was then calculated by taking the net force divided by the surface area of the measuring device, plus the estimated skin friction for the defined flow conditions, as follows:

$$\tau(\text{total}) = \{ F(net)/\text{Surface Area} \} + 0.04 \text{ (psi)}$$

Note: 0.04 psi is the skin friction across the surface of the measuring device as calculated by using simple laminar theory.

It was found from the code that an upward misalignment of 20 mil increased the "apparent" skin friction by a factor of 3. Reduction of the step height to 5 mil introduced an error of +5.7%. This is still too high but was considered much more reasonable. As mentioned earlier, a misaligned tolerance of 2 mil is recommended as acceptable.

Another parameter that was varied in the computer model was the length of the gauge. Interestingly, a reduction in the modeled gauge length resulted in an increased in the "secondary" skin friction. Specifically, for lengths of 0.5, 0.25, 0.125 inch the error was 6, 27, and 54%, respectively. These data suggest that the sizing of the sensing surface could also be critical, a parameter which was not looked at by Allen (Reference 8).

Downward Configuration

A downward or recessed misalignment can be viewed as flow over a cavity. Potentially the cavity could be such that a recirculation region might form (Reference 9). For the case of measuring skin friction, this recirculation region would be seen as "negative" skin friction. Consider the case presented in Figure 10 as modeled using the Marquardt code. In this figure a downward misalignment of 20 mil and a gauge width of 0.5 inch is modeled. The cavity or modeled recessed gauge is such that the flow passes over it, resulting in a zero or negative skin friction.

For a downward misalignment of 5 mil, as presented in Figure 11, the flow has established itself onto the recessed region, forming only small recirculation zones in the two corners.

4.1.3.3 Material Sciences

The material science group was requested to provide a trade-off study to determine which material is best suited for the cantilever beam and the thin film device. Presented here is their recommendation for the cantilever beam. Required of the beam is high stiffness, low coefficient of expansion, oxidation resistant, and property retention above 1000°F, the projected wall temperature.

The mechanical and physical properties of several classes of materials were reviewed. A complete presentation of the properties in tabular form is found in Table 1. The list includes titanium and it's alloys, a low carbon stainless steel (S.S.), beryllium, ceramics, and fused quartz.

Because of the low coefficient of thermal expansion (CTE) with acceptable stiffness and strength properties, the two classes of material most attractive are ceramics like Hexaloy SA (SiC) from Carborundum, PY6 (Si_3N_4) from GTE, and fused quartz (SiO_2) from Mindrin Precision. For comparison, the CTE for the carbides is approximately 6 times higher than for fused quartz, and the CTE for 304 S.S. is 34 times higher than for fused quartz.

Commercial fused quartz (T08) may be purchased in the desired "rod" form here in California for less than $100 per rod, with a two week delivery time.

The materials group recommends fused quartz because of it's low CTE, oxidation resistance, sufficient strength at 1000°F, good fabricability and availability.

Another parameter that must be considered before the final decision of material(s) can be made is the thermal conductivity (k). Presently the device assembled at VPI for testing at NASA-Langley was composed of a S.S. beam configuration which was chosen in an effort to more fully match the heat transfer characteristics of the gauge to the surrounding test rig.

Since this matching or "simulating" of the appropriate heat transfer characteristics of the gauge is essential to maintain Reynolds' analogy, the choice of beam material or combination of materials is critical. For example, if a low k is desired, then fused quartz would be a good choice (50 times less than S.S.). If a high k is desired, then a silicon carbide (Hexaloy SA) would be appropriate (6 times more than S.S.). On the other hand, due to fabrication and assembly constraints a more common material like S.S. might be acceptable.

4.1.3.4 Structures and Design

The Structures and Design groups were able to provide some valuable analyses to further the understanding of Design A. The first task undertaken was to clarify that given VPI's preliminary dimensions for the cantilever beam, the motion of the head would not cause considerable misalignment problems. It was verified that for a beam of several inches long and a head deflection of 1 mil, the misalignment problem due to the bending of the beam is negligible. This further verifies the findings of the university personnel (see Section 4.1.4).

Further studies were made of the VPI preliminary design. Interaction and correspondence between Marquardt and VPI addressing several design issues resulted in a more complete configuration. These improvements were integrated into the prototype device that was tested at NASA-Langley. This testing will be presented in Section 4.1.4.

In response to the specification "guidelines" which were included in the Air Force SOW, the issues of vibration compensation and mechanically rotating the device to check for zero drift were addressed.

Vibration compensation is a very important issue when relatively large facility excitations are experienced. Recent works by the author (Reference 10) at Calspan and Dr. Tcheng at NASA-Langley have been done in this area. For the cantilever beam design it is proposed that a compensating beam be incorporated into the device which would only sense the vibration of the environment. Essentially the gauge would have two beams mounted back to back. One beam would respond to skin friction and vibration, and the other only vibration. Subtracting one output from the other leaves a skin friction measurement. This clever technique was effectively developed at Calspan twenty years ago (Reference 11) for use in a shock tunnel facility.

All skin friction measurement devices which have been developed at VPI over the last 20 years have not needed vibration compensation due to their low frequency (<200 Hz) response. It is believed that if the device to be developed for the Air Force is to have a resonance of 1000 Hz, then some mechanical vibration compensation feature may be required. Further evaluation of the relative magnitude of facility vibration components when compared to typical skin friction outputs is needed. If compensation is required, then a system similar to the Calspan device could be designed.

Contact has been made with Dr. C. Nachtigal and K. Mesterton at Kistler-Morse regarding this issue of vibration compensation. Though it was clear that they have not used their product with vibration compensation, they were supportive of the idea to design a device that could be used. Potentially a compensating device could be manufactured by Kistler-Morse and then integrated into Design A.

Another design issue which was addressed was mechanically rotating the device 180° to check for zero drift.

Some of the concerns are:

- Misalignment due to the rotating part (a couple of mils is believed to be a concern).
- Problems with "piloting" and "locking" the device before and after rotation.
- Sealing the device against the hot gases is a concern. Any leakage can result in almost instant burning of the hardware. Marquardt has experienced some terrible burn-throughs due to minute leaks.

- To protect the hardware and match surface conditions of the gauge to the combustor, the rotated section will probably need to be cooled. Here is another problem to overcome.

From the studies conducted it is recommended that rotation could be incorporated into the design but that this feature should be considered as a follow-on item. Since zero drift is the real issue, then the immediate concern is to identify and then solve this potential problem.

4.1.4 Technical Analyses at VPI

Work at VPI centered around the continued development of a prototype of Design A. As mentioned, the addition of active cooling allowed an earlier version of the current design to operate in a high temperature environment. That early work began as an SBIR project to develop a gage for the hypersonic tunnel at WRDC. The project was never completed due to a tunnel failure. The effort was continued and some preliminary tests were made at the NASA- Langley supersonic combustion facility for which it was designed. These tests showed that the design was sound and that very accurate measurements could be made. A refined design was constructed and tested during Phase I. This design can be interpreted as one realization of a gauge that has potential to meet all requirements specified in this contract. These requirements were addressed during the Phase 1 work, although not all were integrated into the design of this particular gauge. The final, Phase 2 design will meet every requirement as specified.

The relatively simple overall configuration is shown in Figure 12. The sensing head responds to tangential shear from the passing flow which is registered by the sensor. The head is mounted on a stainless steel rod which is connected to the tip of the sensing unit, a Kistler-Morse piezoresistive strain sensor. The Deflection Sensor Cartridge (DSC) is a complete multi-purpose displacement transducer which has the property of being very sensitive while still being stiff. The DSC-6 sensor being used, which is dual axis sensitive, precisely measures the minute deflections in two orthogonal directions simultaneously. The sensing head at the flow surface has a diameter of less than 1/4 inch and a .004 inch gap between it and the surrounding gauge housing. Complete drawings of the design are shown in Figures 13, 14, and 15. The outer housing is lined with a one-inch long channel for running room temperature water around the head assembly. Also, the internal cantilever rod above the sensor is covered with fins and the entire internal assembly is immersed in a cooling fluid. This active cooling system is necessary for the safe, accurate operation of the DSC sensor. Set screw holes were placed at the base of the flange and at the bottom of the water channel for access to the internal housing. These openings were used for injecting fluid as well as for inserting a thermocouple into the inner housing to monitor the temperature at the tip of the DSC-6 sensor.

The fact that the gauge is small, having an overall length of 3 inches, means that the gauge can be mounted in tight locations. The gage can be mounted in any orientation; however, due to the presence of the internal

fluid, the unit works best if the sensing head sits up or sideways with respect to the duct, rather than hanging upside down from the duct top. This unit, once assembled, is not delicate, meaning there is virtually no way to deflect the sensing unit past its operational limits. The head moves only the width of the .004 inch gap before stopping which is well below the maximum deflection allowable for the DSC-6 sensor. Please note that the sensing head must be made to the exact specifications of the facility in which it will be placed. Common material is necessary for the head to simulate the surrounding tunnel wall conditions. One advantage of a small unit is that the sensing head can be made to any contour for measurements needed on curved flow surfaces.

During the design of this gauge, several potential error sources were analyzed. As always, when using a floating element device to measure deflection, misalignment effects are a concern. Also, errors can be introduced due to gap size, lip size and pressure gradients between the flow and the underside of the element. As mentioned, these concepts are discussed at length in the study by J. M. Allen in Reference 8. During heating, the thickness of the sensing head sees no active cooling and may expand vertically into the flow field, causing misalignment error. Ideally, the head is aligned two or three thousandths below the wall surface to counteract the effects of expansion. This expansion is estimated to be on the order of four to five thousandths for a half inch of carbon steel heating 1000°F.

For this particular design, the gap size is large in relation to the diameter of the sensing head (G/D = .0165), which makes the unit less sensitive to misalignment. In Reference 8, Allen states that, "The effect of gap size virtually disappears at zero misalignment". In Figure 7 of Reference 8, this is shown to be true for a gap to diameter ratio above .005. The present ratio of .0165 is far above this indicating no problems due to gap size can be expected. Then, in relation to gap size, effects due to lip size must be considered. The effects of misalignment and lip size are given in Reference 8 in terms of the boundary layer thickness. These data are not available for the current test conditions. However, Figure 10 of Reference 8 indicates that the sensitivity to misalignment decreases as gap to diameter ratio increases. For our case, a lip ratio of .04 and the gap ratio of .0165 together produce a gage insensitive to effects of misalignment.

Errors introduced due to the deflection of the cantilver beam were also considered. The expected deflection of the sensor is .00005 inch which is approximately .0001 inch for the extended beam. The effective angle of deflection is .002 degrees which produces a protrusion of 4 micro inches into the flow (assuming the center of the sensing head is flush with the wall). This cannot contribute any distinguishable pressure gradients developing due to protrusion. Another significant consequence of the small overall deflection is that no self-nulling is required for the gauge.

Internal cooling was obtained by filling the internal housing with a combination of liquid metal and silicon oil. Originally, it was proposed that GIT be used for the entire length of the cantilever. This mixture is liquid at room temperature, although pure gallium is not. The GIT has good heat

conducting properties and a high surface tension. However, using GIT turned out to be impractical when it was found to oxidize readily even in the presence of oil. Ultimately, liquid mercury was injected into the lower part of the housing (surrounding the sensor tip) up to the fifth cooling fin from the bottom. These fins were made out of stainless steel to prevent amalgamation. The upper fins were made of brass for good heat conduction. Dow silicon (1000 cs) oil filled the upper part of the channel and the gap around the sensing head. The high-viscosity oil was used to slow the leakage of the oil out of the .004 inch gap around the sensing head; a problem seen in previous tests when Dowtherm with a lower viscosity oil was used. Therefore, in this case an additional precaution was taken to reduce this potential leaking. Before the actual tests were run, the gauge was placed in a vacuum chamber and brought down to one psi to force any trapped air bubbles inside the assembly to rise and be replaced with oil from a reservoir sitting on the sensing head. This eliminated the tendency of the gauge to leak. Also, removing air bubbles prevents problems of oil ejection during supersonic tunnel starting. In addition, the oil plays an important role in damping. It prevents excessive vibration of the gage during testing. To match the tunnel wall at NASA Langley, a 0.5 inch thick head had to be used. That resulted in a low natural frequency of the unit (~ 150 Hz). However, with the damping no problems were encountered in actual tests.

A direct force calibration was conducted using standard weights and a digital voltmeter. The gauge was clamped nearly vertical so that by hanging the weights directly to the sensor head, the sensor is pulled in the streamwise direction. Outputs in millivolts were read in streamwise and cross-stream directions. The applied weights ranged from 10 mg to 10 grams. The curves remained linear and constant after repeated calibration as shown in Figure 16. The presence of oil in the gage did not affect the calibration.

The tests were run at NASA Langley Research Center's vitiated Heater Facility. The test cell configuration consisted of a Mach 2 nozzle, and a rearward-facing step injector block with a 0.24 inch diameters, perpendicular injection port. The duct diverges at an angle of three degrees on the top side while remaining flat at the bottom. Three optical access stations are evenly spaced within the duct, of which the farthest was used for inserting the gauge into the duct. The gauge was mounted in a plug that fit into the existing duct opening. Cooling water was run from a tap through 100 ft. of copper tubing immersed in a 55 gallon drum before reaching the gauge to insure a constant water temperature of 60°F. Tunnel conditions for this test registered nominally a static temperature of 2200°R and static pressure of 8.83 psi at the measurement station. The local Mach number was 1.74.

The normal test cycle for the test cell consists of several steps leading to the actual fuel burning phase. First, 50 psi air is pumped continually through the tunnel to purge any possible build-ups of hydrogen in the test cell. The air ejector is turned on, and then the heater is started and allowed to stabilize before the full fuel is injected perpendicular to the flow.

During preparations for testing the gauge, mechanical difficulties arose with the soldered copper pipe joints on the water channel sleeve. Due to the particular testing arrangement in the test cell, extreme caution was needed in the area where the gauge was mounted. The work space was extremely limited.

Therefore, the cooling system was modified to incorporate one continuous length of copper tubing. The gauge was then safely and easily mounted in the test cell without incident. The actual tests were then run repeatedly on one day without the gauge being disturbed between runs. The experimental set-up consisted of the gauge wired in both axes directly to a bridge completion box which converts the signal to an output voltage. The gauge was powered by a +6 volt power supply and the output measured on a Lineis strip chart recorder. The recorder was initially set to a zero for each axis and run at a speed of 20 cm/min throughout each test. In order to explain the strip-chart data, Figure 17 is included to show how the dual-axis sensor is oriented with respect to the flow. Actual recorded outputs for two individual test runs are shown in Figures 18 and 19. These show the initial detection of output at the start of the low-flow air, the vibration of the tunnel that was picked up when the ejector was turned on, the signal jump due to the igniter, and the peak when the ejector was turned on, the signal jump due to the igniter, and the peak when the fuel was added. Note, that damping from the cooling fluid limited vibrations to a small percentage of the total signal.

Average outputs for the gauge during the eight second fuel burn time were compared with the pre-test calibration and were found to fall near the center of the calibration scale. These outputs were converted to forces and combined with calculated tunnel conditions to produce a skin friction coefficient. These calculations are included in Table 2. Preliminary estimates indicate that these results are accurate to between ± 5 and 10%. Note that an axial component of wall shear and a smaller transverse component were both successfully measured. These data are believed to show the real situation, since the fuel injection scheme for these tests was asymmetric. There was a single fuel injector in the top wall.

The water-cooling during the actual testing proved very effective. Thermocouples attached to the copper tubing at the water input and return points registered a constant temperature within ± 2°F, the sensitivity of the thermocouple. The thermocouple measuring the internal temperature of the gauge registered no change throughout the test cycle. The oil and mercury effectively dissipated the heat passing through the sensing head into the cantilever rod. Thermocouples attached to the outside of the duct at the same streamwise location as the gauge registered above 600°F during the fuel burn. The sensing head of the gauge would have seen at least this temperature. It is reasonable to suggest that the cooling system as currently set up can handle significantly higher duct temperatures.

This Design A prototype has been successfully tested with consistent results. Further analysis of this data will be used to identify problem areas and to motivate design improvements. The information obtained during these tests insures that the Phase II design will be able to meet the specified requirements for the gauge.

4.2 DESIGN B - THIN FILM

This design draws on the experience of Drs. Diller and Wicks in the areas of heat transfer and strain gauge technology, respectively. Dr. Diller is also involved in the development of a new heat flux sensor which exploits high vacuum sputtering technology to fabricate a "thin film" heat flux gauge. This technology is the basis of Design B.

The important characteristics are that the design has negligible surface disruption, it is a direct-reading force gauge giving both magnitude and direction, it has high frequency (kHz) response for time-dependent measurements, and possesses a high temperature capability (1000°F).

4.2.1 Functional Operation

This design is based on the use of sputtered strain gauges to sense the effects of the test model skin friction. As presented in Figure 20, the device comprises a thin (0.001 in.) square sheet of metal or "wafer" which has a strain gauge sputter-coated onto the surface of each tab. The wafer is restrained at each corner. It is believed that as the gas-flow passes over the surface of the wafer, the strain gauges produce output which can be related to the magnitude and direction of the skin friction.

There will be a thin (approximately 8.0 micro-in.) electrical insulating layer of a ceramic (e.g., aluminum nitride) sputter-coated underneath the strain element. The strain in the tab is measured by the change in resistance of metal composing the strain element (e.g., nickel, silver, or platinum). The signal from each is brought out through two leads at the end of each tab. The tabs will be enlarged at the end to accommodate the leads and to aid in connection to the surface. The remainder of the skin friction gauge is free floating with respect to the surface. When the gauge is initially connected to the surface, the tabs are all placed in tension.

The tabs are made narrow relative to the rest of the gauge (0.4 in. X 0.4 in.). The shear force acts over the large central portion of the gauge, which is supported only by the much smaller tabs. Therefore, the force is localized in a small area causing measurable strain.

At least one sputtered thermocouple is placed on the skin friction gauge to allow for temperature compensation of the output, if needed. Because the gauge measures the force imbalance between opposing tabs, the resistance change of the strain elements with temperature will exactly cancel if the gauge is at a uniform temperature. This is a major advantage of this gauge when used for high temperature measurements. However, the sensitivity of the resistance to strain may change with temperature and, therefore, compensation of this may be necessary. This correction should not be large.

All of the strain elements including the surface of the feed-through leads are then covered with a layer of ceramic (e.g., aluminum nitride) to protect the elements from physical damage. The last coat must be sputter-coated with the gauge mounted on the surface. In fact, all of the sputtered layers would be applied after mounting has been done achieved.

4.2.2 Critical Design Parameters

The following are the critical design parameters which have been identified.

1. Aerodynamic issues surrounding this design are somewhat different than for design A. If the wafer is free floating with respect to the surface, then gas could flow underneath creating numerous potential problems. As stated for design A, any obstruction into the flow will cause some boundary layer perturbation. If the gauge can be made very thin, and recessed, then this effect can be made negligible.

2. Heating effects upon such a small device are of great concern. Since the wafer is free-floating, it is estimated that the gauge could approach the recovery temperature of the gas-flow. Without some cooling, the tabs, strain gauges, wafer, attachments, and lead wires are all going to experience the extreme temperatures. It is proposed that a "medium" be placed between the wafer and the wall to aid in heat transfer.

3. The methodology of attaching the tabs to the surface of the model has yet to be determined. Conventional adhesives are limited to about 500°F, therefore, some other technique will be required.

4.2.3 Technical Analyses At Marquardt

Analysis of Design B was performed under the matrix organization, as was carried out for Design A. Many of the design issues related to Design B have already been presented for Design A and will only be mentioned briefly.

4.2.3.1 Heat Transfer

As presented in Section 4.1.3.1, a transient heat transfer model of Design B was developed. The immediate task was to establish the effect of different fluids that could be used to fill the gap between the wafer and the combustor wall. The same heating scheme from Design A test runs was used. The simulated thin film gauge (5 mil thick) was mounted into a 1/4 inch thick S.S. plate. The plate was cooled by water spray on the backside. The first case was with radiation cooling across the air gap. The air properties were taken at 1000°F. Since the thin metal sheet was observed to heat up to 2250°F, a liquid metal (GIT) was added to the gap to aid in cooling. The thin sheet temperature was observed to fall to a much more acceptable temperature of 645°F. This surface temperature compared to within 20°F of the case for an all S.S. wall. This result shows that the use of a liquid metal in the gap between the thin sheet and the model wall will simulate very closely the surrounding wall conditions. For a comparison of these cases, see Figure 21.

Analysis of an oil, like VP-1, was not carried out due to the fact that the boiling point of these fluids is approximately 800°F. It is believed that the oil would only boil or burn out of the gap which would leave the wafer to heat up to the "air in the gap" case.

4.2.3.2 Aerodynamics

The discussion presented in Section 4.1.3.2 is also pertinent to the aerodynamic concerns for Design B. Again, this design is a "direct" measurement device with potential misalignment problems similar to Design A. It can be argued that this design has fewer parts and is much simplier and therefore presents a less severe problem. To minimize aerodynamic problems and improve heat transfer capability the wafer will be recessed into a machined pocket and a fluid (possibly a liquid metal) placed in the pocket.

4.2.3.3 Material Sciences

The materials science group have recommended the use of a metal sheet for the wafer. Ceramics are much too brittle for such an application and the thermal properties would not allow for matching of the wall temperatures. The materials for sputtering the micro-strain gauges will have to be determined following further analysis. There is work going on at NASA-Lewis in this area of high temperature sputtering. They have reported sputtering platinum-rhodium thermocouples to measure surface temperatures up to 1790°F (Reference 12).

4.2.3.4 Structures and Design

Design B was reviewed by the structures and design groups. Question was raised about the ability of a machine shop to fabricate such a small item as the wafer and then cut the small recessed pocket. A local company here in California was located which revealed that they could hold the required VPI tolerances by the use of Laser machining. It is proposed that an "actual" size prototype be fabricated in the follow-on work to demonstrate the design.

Another issue addressed is the attaching of the wafer to the wall. It is proposed that a ceramic adhesive could be used to attach the tabs.

Vibration compensation for this design is argued to be unnecessary. Due to the stiffness of the tabs and the low mass of the wafer, the gauge will be relatively insensitive to vibration.

4.2.4 Technical Analyses at VPI

A 10X prototype of the thin film gauge was constructed and mounted to a base plate, with no fluid between the gauge and base plate. Static and steady-flow calibration, along with unsteady-flow measurements were performed using this prototype. The prototype consists of a 0.001 inch thick sheet of stainless steel shim stock with a sensing area of 4 inch x 4 inch. The tab widths are 0.125 inch with standard strain gauges mounted on each tab. Two adjacent tabs are secured to the base plate through the use of small screws. The other two tabs are fastened to adjustable slide plates which can be used to adjust the amount of preload in each tab (Figure 22). The leads from each strain gauge are connected to a bridge amplifier circuit.

Static calibration of the prototype began by loading the gauge statically from the gauge center, and recording the differential strain gauge output from each axis of the gauge. The static calibration was performed to relate the gauge output to the actual force acting on the gauge surface. A line was attached to the gauge surface and loaded in increments of approximately 30 grams. A maximum static load of 1 lbf was applied, then the gauge was unloaded in the same increments. Linearity of the output and hysteresis effects were examined with results shown in Figure 23. Using a 100X amplifier, a sensitivity of 0.92 v/psi was obtained. The results were linear and repeatable, but the output was sensitive to the line attachment position. This is an expected result of the directional sensitivity of the gauge. The hysteresis effects are small, indicating that frictional effects between the gauge and base plate are small. The output of the gauge is also sensitive to the amount of preload in the tabs. A preload of 2 lbf was used in the above tests.

Steady-flow calibration of the thin film gauge was performed in a low speed wind tunnel with a velocity of approximately 20 m/s. The voltage output of the thin film gauge was compared to the static calibration results to obtain the shear force acting on the gauge. Unexpectedly large output was initially obtained from the thin film gauge when compared to measurements made with a Preston Tube. The thin film gauge was observed to experience separation from the base plate at higher velocities. Therefore, shear forces acting on the underside of the gauge resulted in high shear measurements. This effect was eliminated by applying a thin layer of oil under the gauge surface. The results were then too small to measure accurately, however, because of the small flow velocities available. Steady calibration will be repeated at higher velocities (100 m/s) in a larger tunnel. The effect of non-uniform temperature changes was also observed during steady testing of the gauge. These effects can be eliminated by monitoring the temperature in each strain gauge with a thermocouple.

The thin film gauge was also used to make unsteady measurements of wall shear stress fluctuations due to vortex shedding from a cylinder placed in the flow field. The shedding frequency of 95 Hz was detected by the thin film gauge as shown in Figure 24. A comparison of the phase and magnitude of the thin film gauge output with velocity measurements obtained from a hot-wire anemometer are shown in Figure 25.

Steady and unsteady testing of the 10X prototype will continue to compare the thin film gauge output with current skin friction measurement techniques. A test apparatus is currently being developed to compare the output of the thin film gauge, a cantilever beam (Design A), and a Preston Tube. These tests will be performed at flow velocities of approximately 100 m/s. A steady calibration of the gauge will be obtained by comparing the output of the various measurement techniques over a range of flow velocities.

Testing of a 10X prototype, fabricated from 0.005 inch stainless steel shim stock, in supersonic flow condition (M = 2.4) is expected to begin in the following weeks. The gauge is recessed flush with the plate to eliminate shock formation and pressure effects at the leading edge of the gauge. Side-by-side testing of the thin film gauge and Design A will compare the output obtained from the two measurement techniques.

Once testing of the 10X prototype has been completed, fabrication of a 1X version of the thin film gauge will begin. Effort must be concentrated in attaching the thin film to the wall with the desired preload in the tabs. Once 1X version has been manufactured, similar testing as in the 10X prototype gauge will be performed.

4.3 SUPPORT ELECTRONICS AT VPI

Instrumentation has been designed to support both Design A and Design B. This electronics package allows for flexibility to condition the output from the respective transducers.

The instrumentation developed to detect the small strain gauge resistance changes of the shear stress gauge utilizes a voltage regulator, a Wheatstone bridge, and an amplifier. The instrumentation is powered by four 9 volt batteries to maintain portability. The combination of carefully regulating the voltage across the bridge and using a precision instrumentation amplifier allows maximum measurement sensitivity.

The regulator used to drive the Wheatstone bridge is the LM723CN voltage regulator. This particular regulator was chosen because of its long term output stability, and its capability of providing different regulated output voltage levels.

The differential amplifier used to amplify the output of the bridge is the AD624BD amplifier. The AD624 is designed using the classical three op amp configuration. It is designed primarily for use with low level transducers such as strain gauges because of its low noise, high common mode rejection ratio, high gain accuracy, low gain temperature coefficient, and high resolution. The AD624 does not need any external components for gains of 1, 100, 200, 500, and 1000, and it has an output offset nulling terminal to maintain high precision measurements.

5.0 DESIGN SPECIFICATION

As stated in the Air Force SOW, the specification for the proposed designs shall be generated. A guideline to the design requirements was provided in the Air Force SOW for Marquardt's evaluation. These specification guidelines were thoroughly analyzed and evaluated against the two design approaches. Presented below is the recommended specification by Marquardt and VPI for the two designs - (A) Cantilever Beam and (B) Thin Film. This specification shall be the basis for a follow-on Phase II - Detailed Design.

5.1 DESIGN REQUIREMENTS

1. Resonant Frequency

   A minimum resonance of 1 kHz is required.

2. Size Requirement

   The diameter of the exposed moving surface shall be less than 0.5 inch.

3. Loading

   The gauge shall be designed to measure a skin friction of 0.05 - 0.25 psi.

4. Maximum Error

   Maximum rms error sensitivity from all sources, expressed as falsely indicated skin friction of ±5% (Section 5.3).

5. Overload Stop Engagement

   An overload stop engagement and indicator of twice full scale loading shall be provided.

6. Output Signal

   The output signal shall be monotonic and non-periodic.

7. Acceleration Sensitivity

   A signal due to 1-g acceleration aligned with the sensitive axis shall not exceed 10% of full scale load.

8. Mounting Orientation

   The gauge shall be designed to mount in any orientation. Of course there will be a more preferred arrangement.

9. Operation Requirement

The gauge shall be designed for testing times which are compatible with current ground test facilities.* These testing times are interpreted to mean "minutes".

10. Utilization Rate

The gauge will be designed for 5 test runs with no refurbishment between runs.

11. Output Terminals

The output system from the gauge must provide signal transmission to the test facility, while protecting the gauge from the surrounding environment. Output wires may be exposed to cooling water spray and other hostile factors.

12. Acceptance Testing

Prior to installation into a combustor the gauge electronics shall pass acceptance testing as specified for each application. (Limited environmental tests, L.E.T.).

5.2 ENVIRONMENTAL CONDITIONS

Presented here are the conditions that the gauge will be required to survive.

- Heat flux of 1 to 5 Btu/sec.-sq. in.
- Surface temperatures as high as 1000°F.
- Airflow velocities of 5000 to 8000 fps.
- Airflow static pressures of 5 to 15 psia.

5.3 SKIN FRICTION ERROR SOURCES

Listed below are the various sources of error that need to be addressed for each design:

- Temperature and temperature gradient effects on zero drift
- Matching the surface temperatures of the exposed gauge and the surrounding wall
- Pressure gradients across the surface of the device

*It is planned that the gauge be mounted on a SCRAMJET engine duct wall which: (1) may or may not be water-cooled, (2) will impose vibration, (3) will subject the gauge sensing surface to starting shocks, (4) will require test item handling. These factors may impose unique design criteria on the gauge depending upon application.

- Internal leakage flow of combustor gases
- Misalignment of moving and non-moving exposed surfaces
- Momentum of coolant on moving parts
- Effects of electro-magnetic radiation
- Strain transmitted from model
- Effects on output from data processing (sample rate, filtering, etc.).
- Hysteresis

6.0 CONCLUSIONS

The preliminary designs of two skin friction gauges have been successfully completed. The pros and cons of the designs were evaluated and specifications were described.

Design cooling schemes were analyzed to allow for matching of the exposed wall conditions with the conditions of the exposed surface of the devices.

At a pace much accelerated over the scope of the outlined objectives, prototype fabrication, calibration and proof-of-concept air flow tests were carried out at VPI. These milestones have shown that both design approaches are feasible means of measuring SCRAMJET skin friction. Marquardt is convinced that the current arrangement with VPI provides the Air Force with an extremely productive team for developing this advanced instrumentation technology. The mutual contacts with principle investigators at NASA and other organizations have contributed to the best possible nationwide effort on this critical SCRAMJET program.

7.0 RECOMMENDATIONS/FUTURE STUDIES

It is proposed that Marquardt continue the development of skin friction gauge technology by the completion of a Phase II - Detailed Design. This effort will span a six-month period with continued subcontracted support from VPI. The specifications for the gauges established in Phase I shall be the design requirements for Phase II. The ultimate objective of the overall program is the development and implementation of skin friction measurement devices for use in the hostile SCRAMJET environment.

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TABLE 1. CANTILEVER BEAM MATERIALS

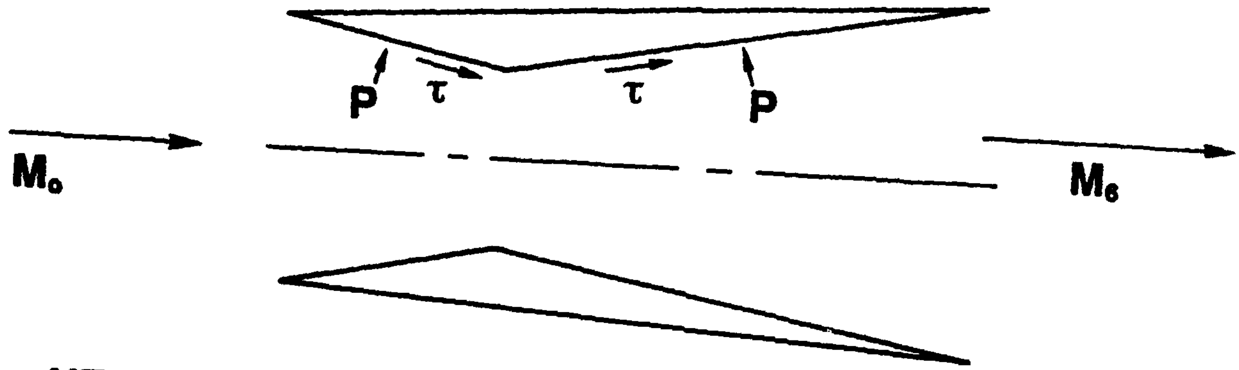
	Pure Ti A70	Ti-6Al-4V	Beta C Titanium	304SS	Beryllium S200E HP20	Beryllium SF200D PS20	SiC Hexaloy SA	Si_3N_4 PY6	Commercial Fused Quartz
Specification	AMS 4921 MIL-T-9047	AMS 4928 MIL-T-9047	no spec	AMS 5639 QQ-S-763 Comp 304, Cond	MIL-B-21531	MIL-B-8964	no spec	no spec	no spec
Density(lb/in^3)	.163	.160	.174	.286	.066	.067	.112	.112	.080
Tensile Strength RT	80	135	190	75	40	65	67*flex	90*flex	7.1
(ksi) 1000F	24	68	125	53	17		67*flex	82*flex	----
Yield Strength RT	70	125	180	30	30	42	----	---	----
(ksi) 1000F	14	56	110	17	13	----	----	----	----
Elong in 2in. (%) RT	15	10	8	50	1	5	----	----	----
1000F	----	24	40	----	9	----	----	----	----
Modulus (10^6 psi) RT	15.5	16.0	14.0	29	42	42.5	59.4	43.5	10.5
1000F	----	8.0	----	23	----	----	----	----	11.0
CTE RT-1000F (10^{-6}in/in/°F)	5.3	5.6	5.4	10.4	6.4	6.4	2.2	2.0	.31
Thermal Conductivity (Btu·ft/hr·ft^2·°F) RT	11.5	4.2	----	9.0	96.0	96.0	84.2	21.7	.16
1000F	11.0	7.2	----	13.0	58.0	58.0	40.2	8.0	.25
Specific Heat RT	.125	.122	----	.120	.435	.435	.16	----	.18
(Btu/lb·°F) 1000F	.160	.180	----	.142	.682	.682	----	----	.23
Condition	Annealed	annealed	STA	Annealed	Hot Pressed Bar	Stress Relieved	Sintered	----	Annealed
Form	Bar	Bar	Bar	Bar	Hot Pressed Shapes	Cross Roll-ed Plate	Rod	----	Bar

* Tensile Strength = 1/2 Flex Strength

0W10e-4

TABLE 2. NASA-LANGLEY SKIN FRICTION DATA

MEASUREMENT STATION CONDITION	RUN 1	RUN 2
Mach	1.74	1.74
Pressure (psf)	8.83	8.79
Temperature (R)	2205	2202
Velocity (ft/sec)	4182	4184
Shear Force (lbs)	0.00407	0.00447
C_{f_x}	0.0051	0.0056
C_{f_z}	0.0009	0.0012



NET JET THRUST $= \left\{ \int P \, dA_{FWD} - \int P \, dA_{AFT} \right\} - \left\{ \int \tau \, dA_{SURF} \right\}$

TYPICAL SCRAMJET PERFORMANCE

- Mo = 8/100000 FEET
- C_f = .002 (ASSUMED VALUE)
- SKIN FRICTION IS 35% OF ENGINE NET THRUST

Figure 1. Scramjet Configuration

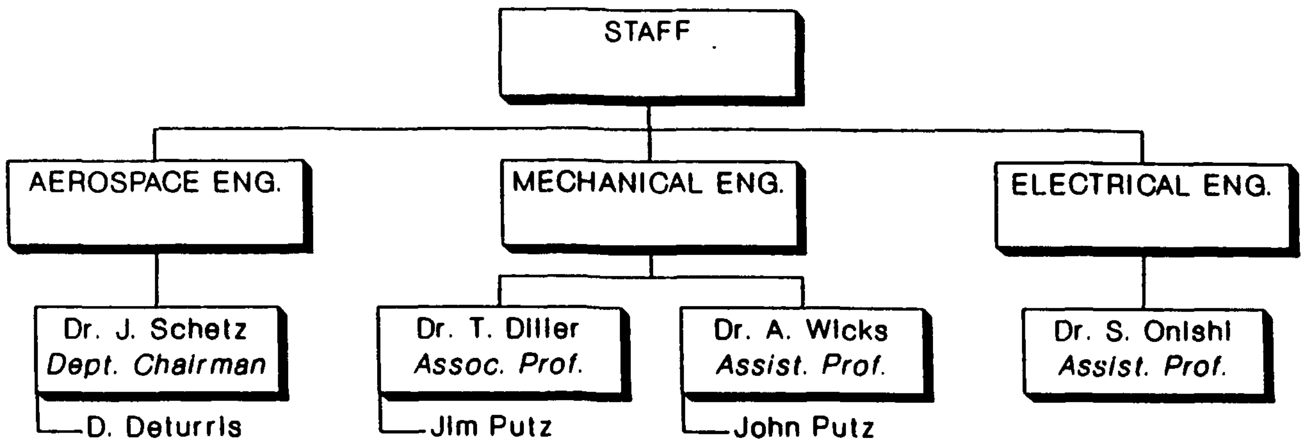


Figure 2. Virginia Polytechnic Institute Research Team

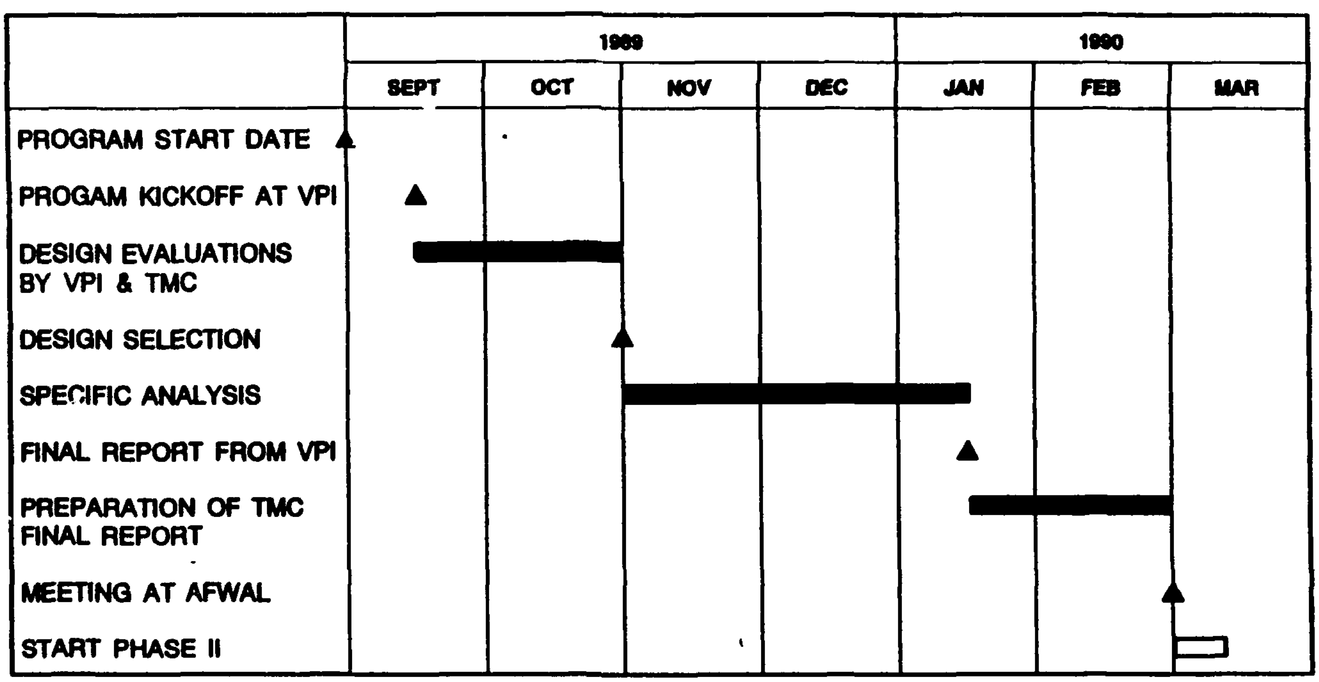
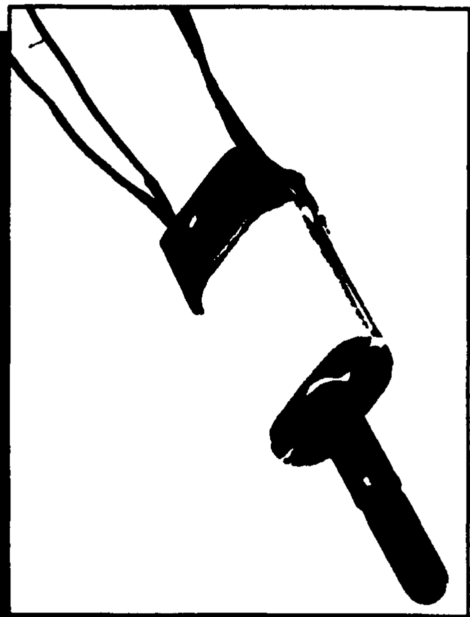


Figure 3. Program Schedule - Phase I

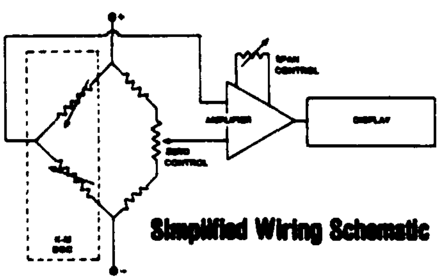


Kistler-Morse®

Displacement Sensor

OPERATING ADVANTAGES

- Compact, Light Weight
- Highly Sensitive
- Universal Applications
- Rugged Construction



Simplified Wiring Schematic

Unlimited use in Instrumentation and Precision Control.

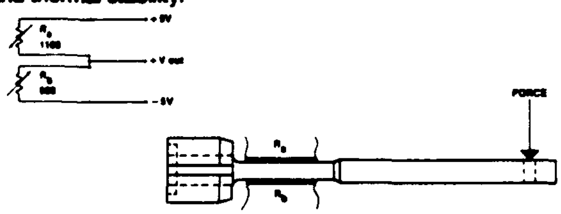
How it Operates

The Displacement Sensor (DS) is a unique, bi-directional, piezoresistive strain sensor used to measure minute deflections caused by a force. As force is applied to the cartridge, two crystals deflect, causing a resistance change. When the crystals are connected in the form of a half-bridge and provided with an excitation voltage, a high level output signal corresponding to the applied force is produced.

The DS may be used for direct measurement or may be incorporated into a transducer as an active element. The DS is virtually unlimited in its application for instrumentation and precision control. It has demonstrated excellent performance and reliability in the measurement of flow, pressure, acceleration, torque and deflection.

Design Concept

The DS consists of a single beam that is machined from stainless steel with two fiber-like silicon crystals glass-fused to the beam. The DS is constructed so that the crystal sensors are put into tension and compression simultaneously when force is applied to the cantilever beam assembly. The sensitive area where the crystals are fused is encapsulated with an RTV compound to protect the fine interconnection wires and to permit normal handling of the sensor. Being of unitized construction, resolution is only limited by practical consideration of mechanical connections and thermal stability.



The two crystals when wired as the active elements of a wheatstone bridge, provide a continuous, highly linear signal throughout the full bi-directional range of the DS.

Temperature Compensation

The natural temperature stability of the DS is 0.3 mV/°F (0.6 mV/°C). Special temperature compensation is available to meet more stringent requirements. Consult Kistler-Morse.

Signal Conditioning

Kistler-Morse supports the DS product line with a varied group of signal conditioning electronics and displays to meet most applications. For your specific needs, consult Kistler-Morse.

KM 20-077, 8/88

Figure 4. Kistler-Morse Displacement Sensor

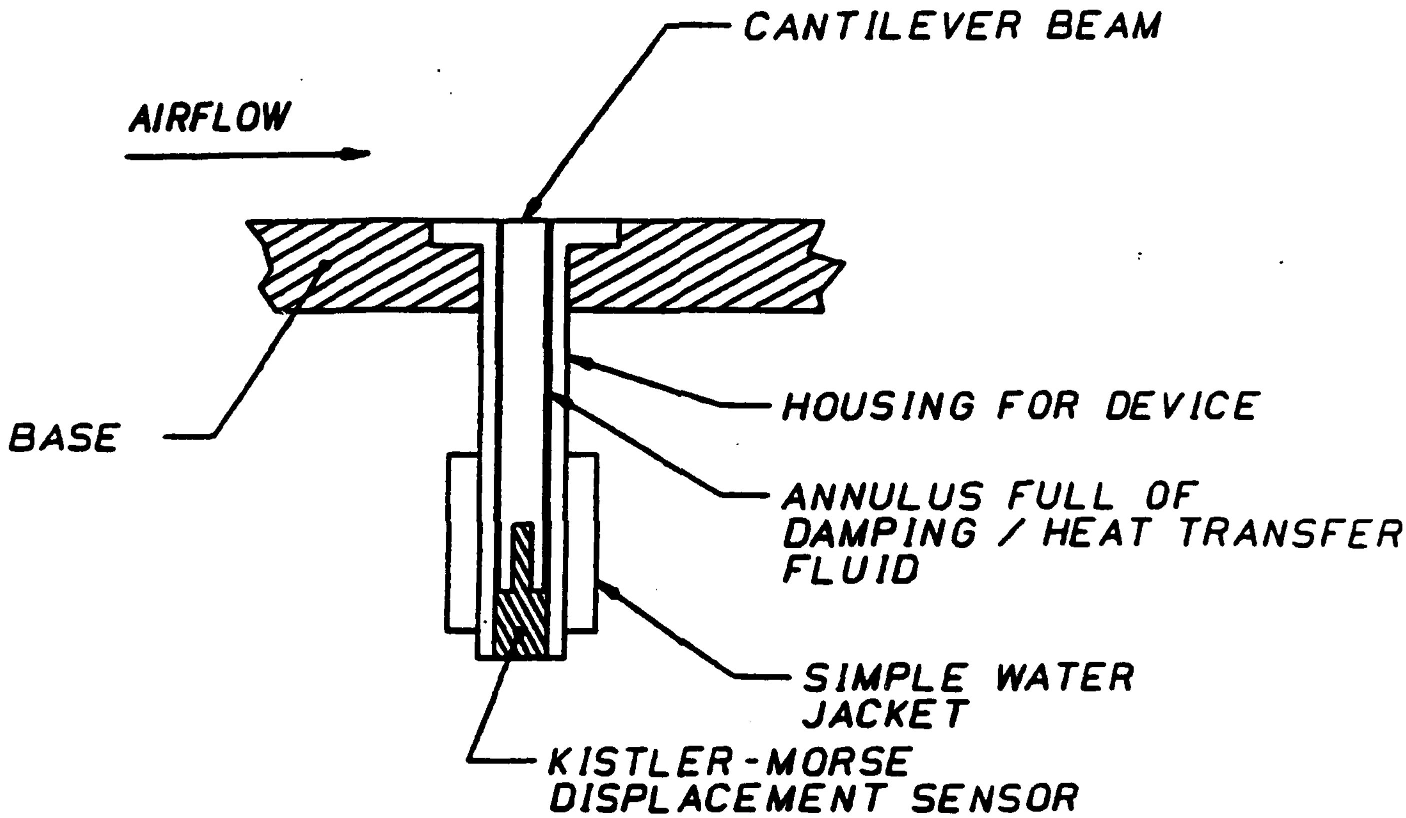


Figure 5. Design A - Cantilever Beam

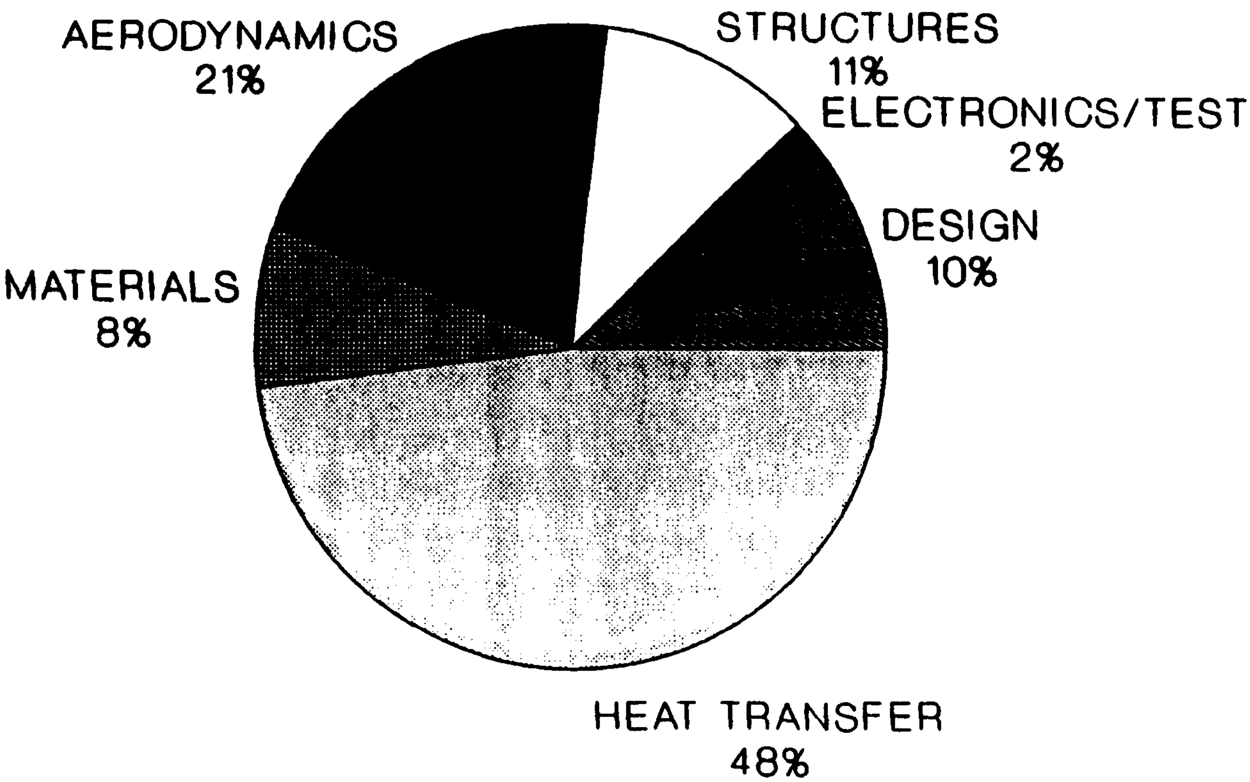


Figure 6. Distribution of Effort At Marquardt (Percent of Hours)

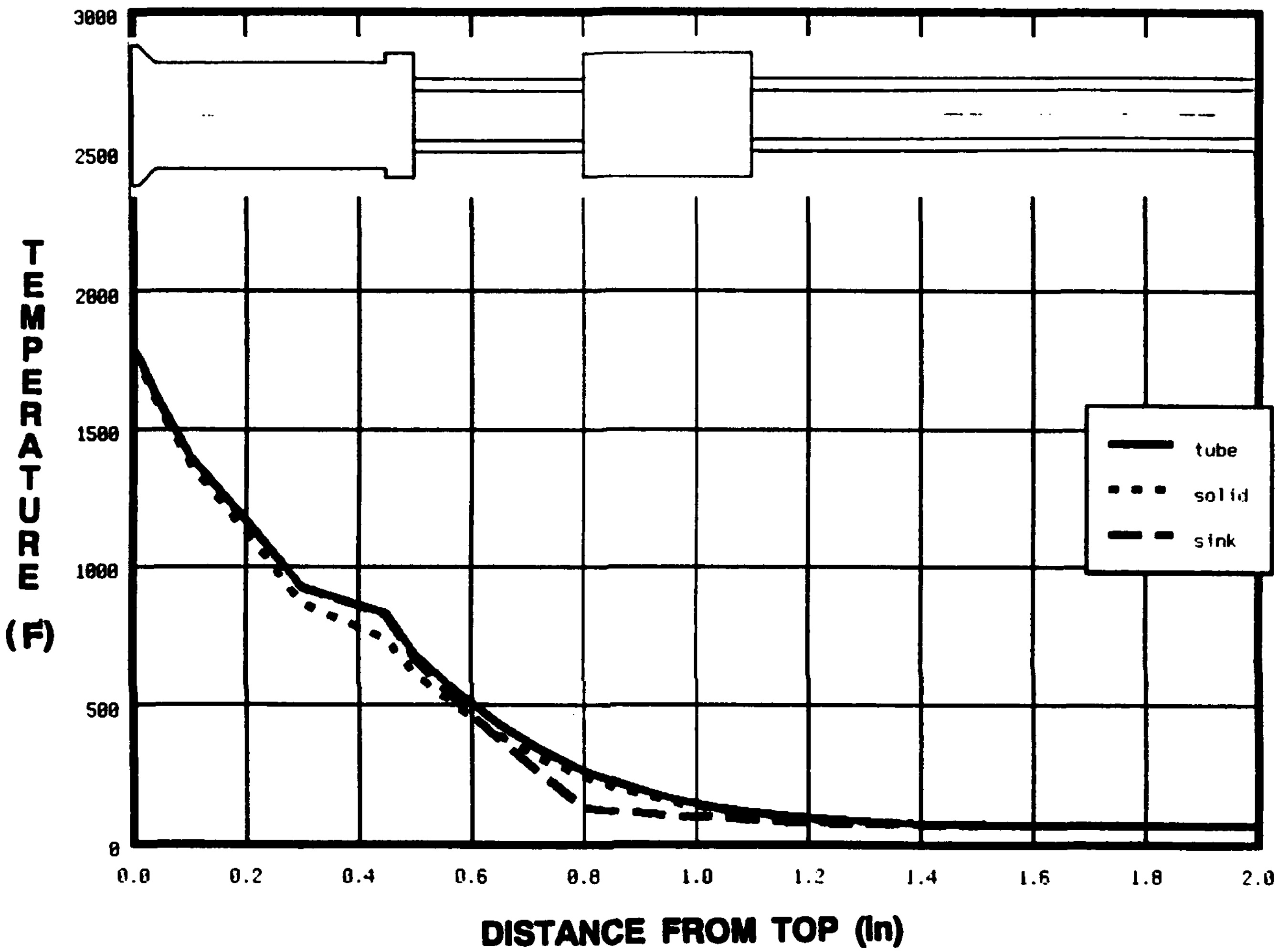


Figure 7. Comparison of Beam Configurations

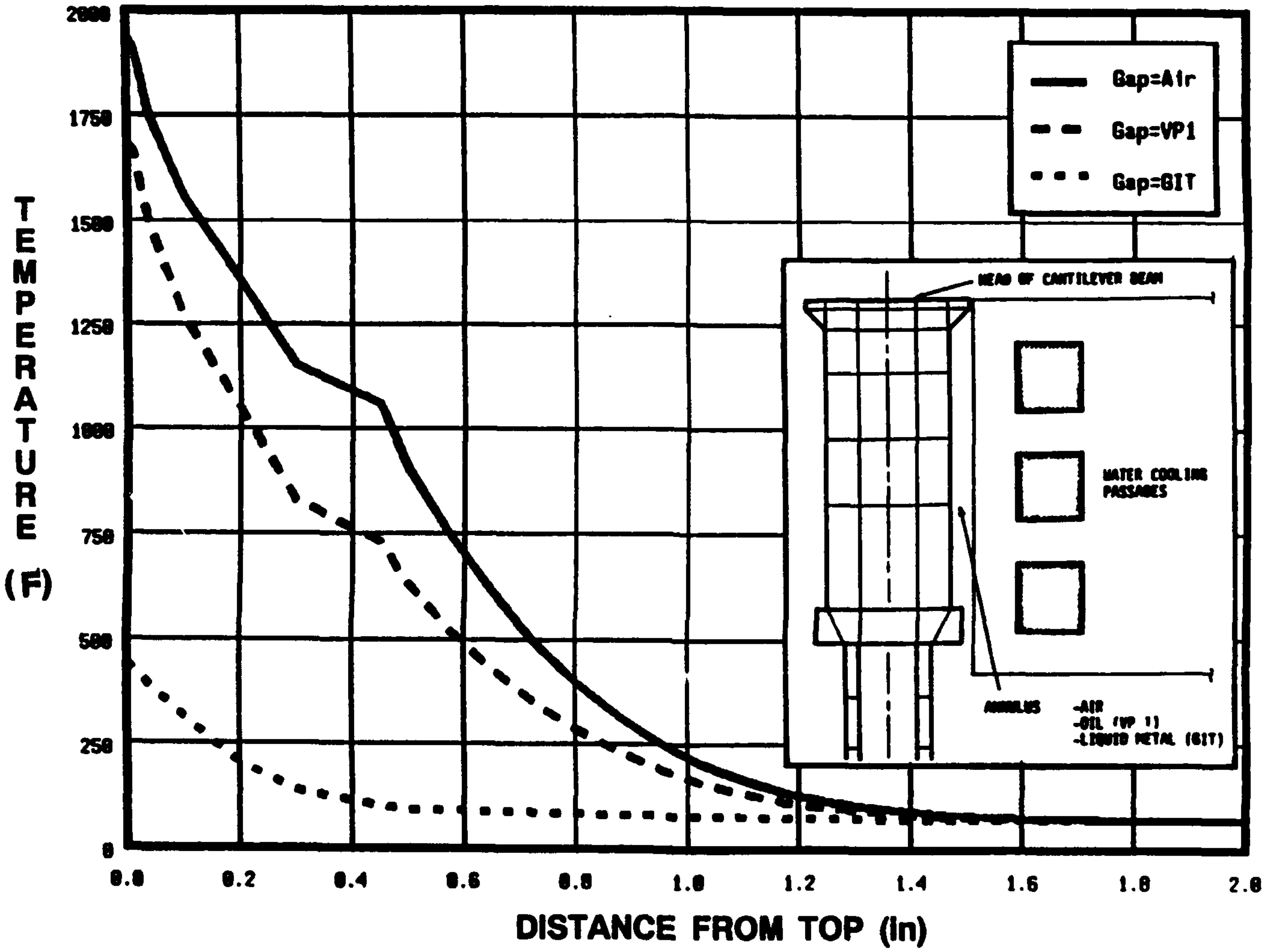


Figure 8. Comparison of Fluids in Annulus

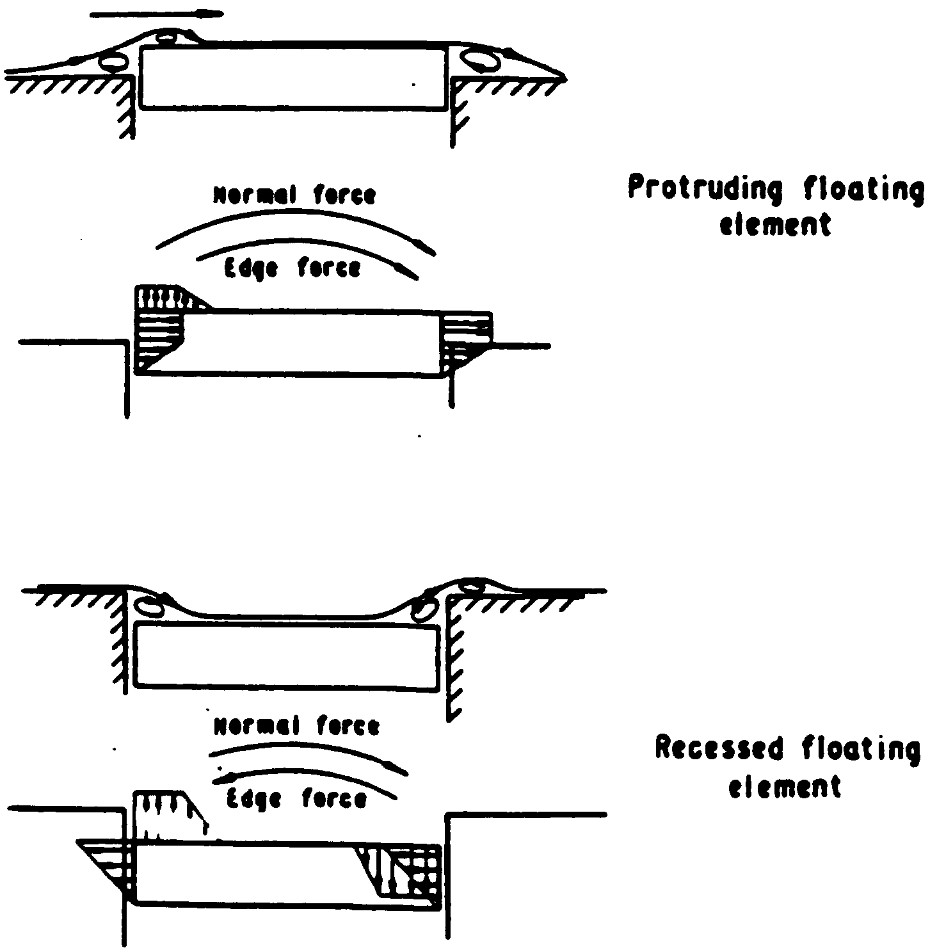


Figure 9. Effects of Misalignment On Gauge (Reference 8)

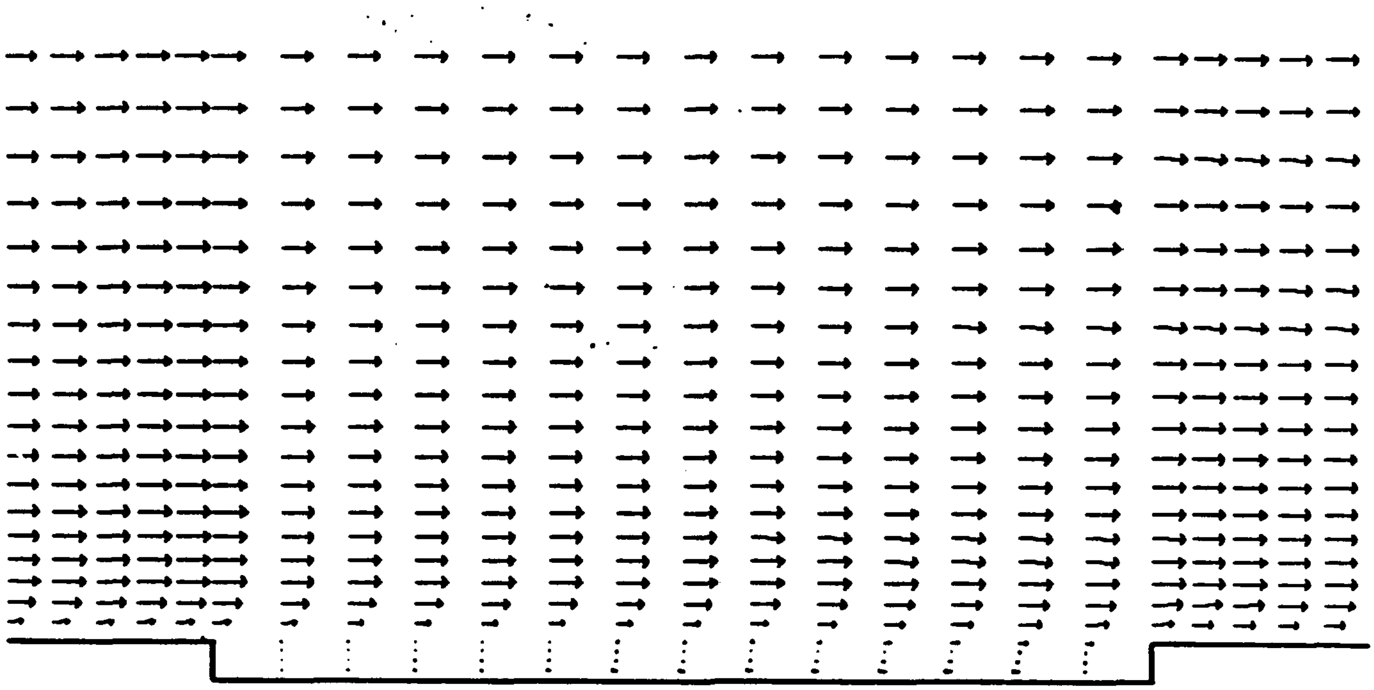


Figure 10. Velocity Flow Field For A Downward 20 MIL, 1/2 Inch Long Misalignment

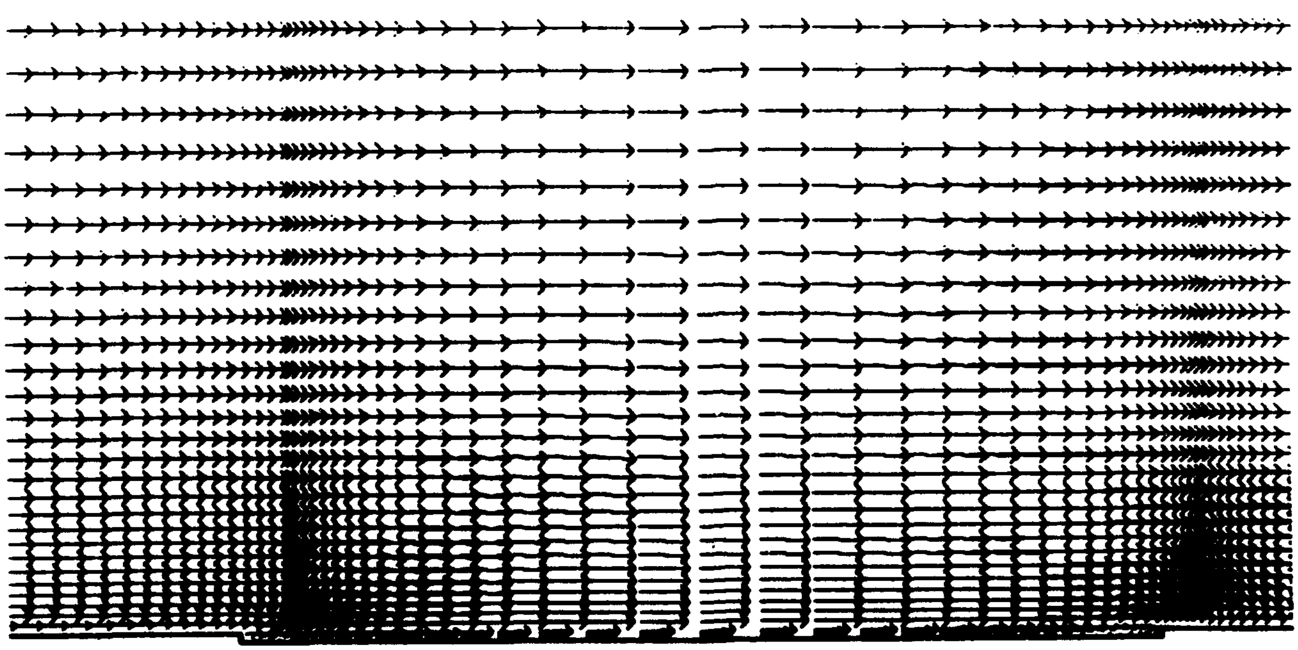


Figure 11. Velocity Flow Field For A Downward 5 MIL, 1/2 Inch Long Misalignment

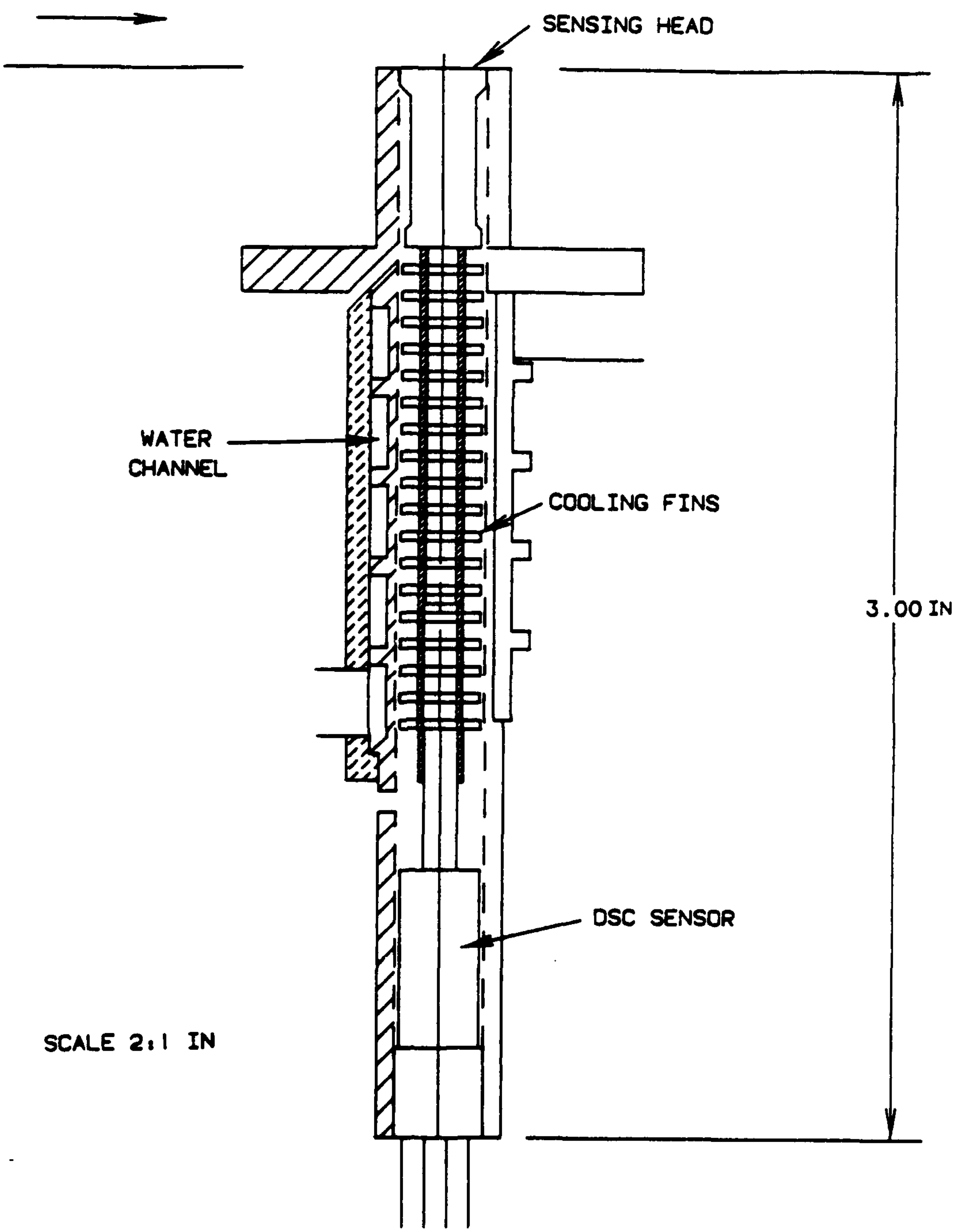


Figure 12. Design A Assembly Drawing

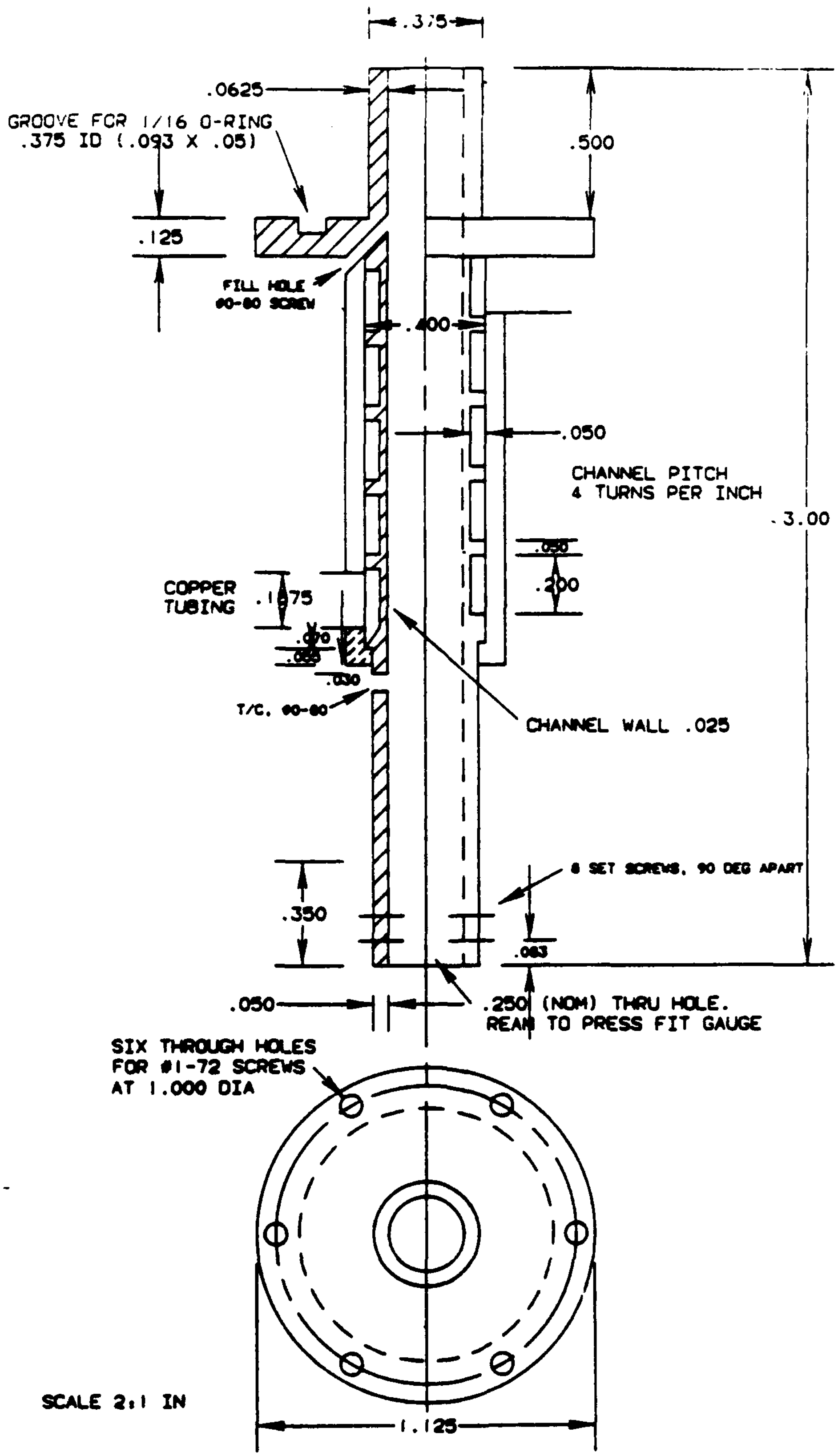


Figure 13. Design A Housing

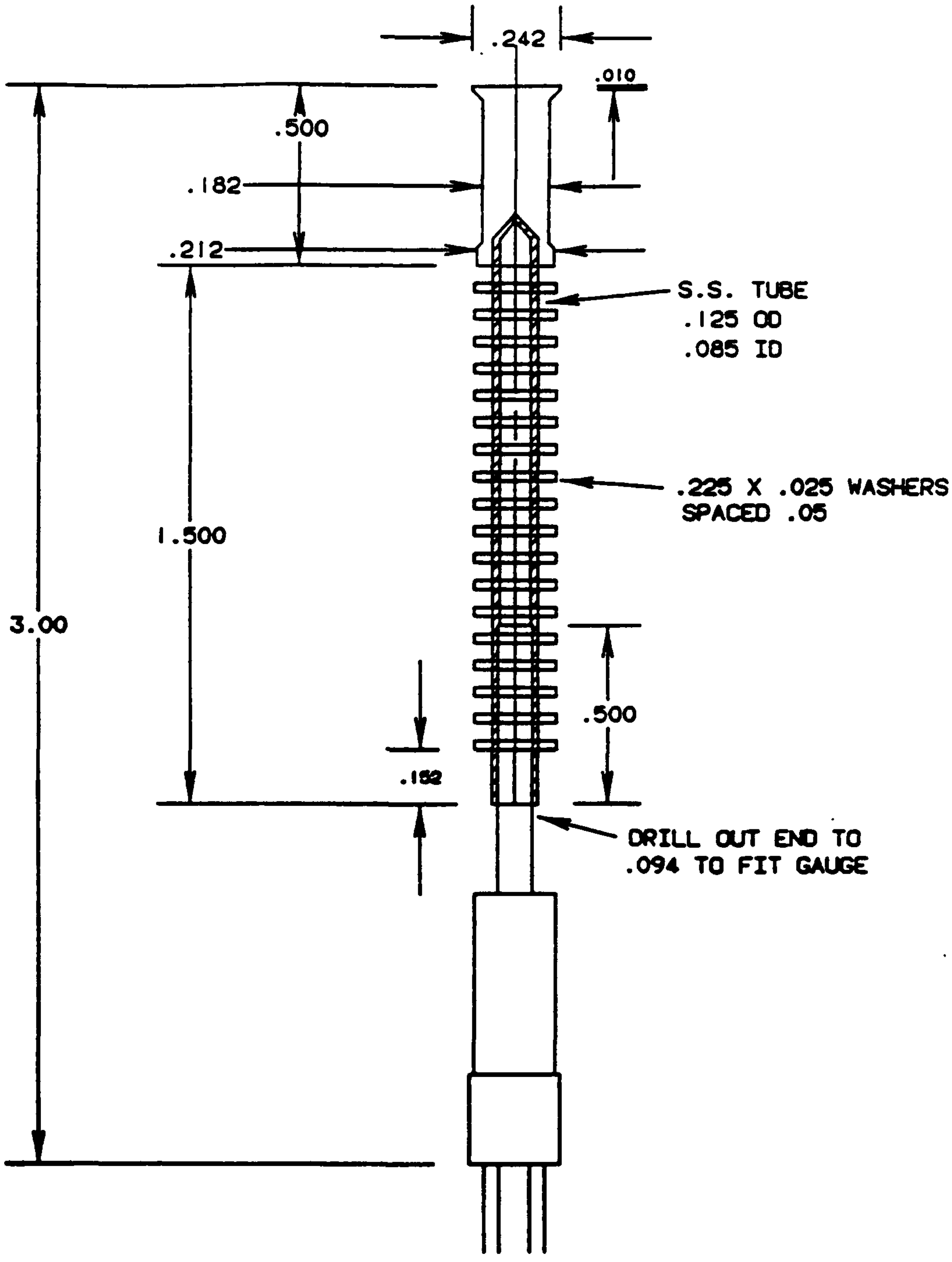


Figure 14. Internal Cantilever Arrangement

SCALE 2:1 IN

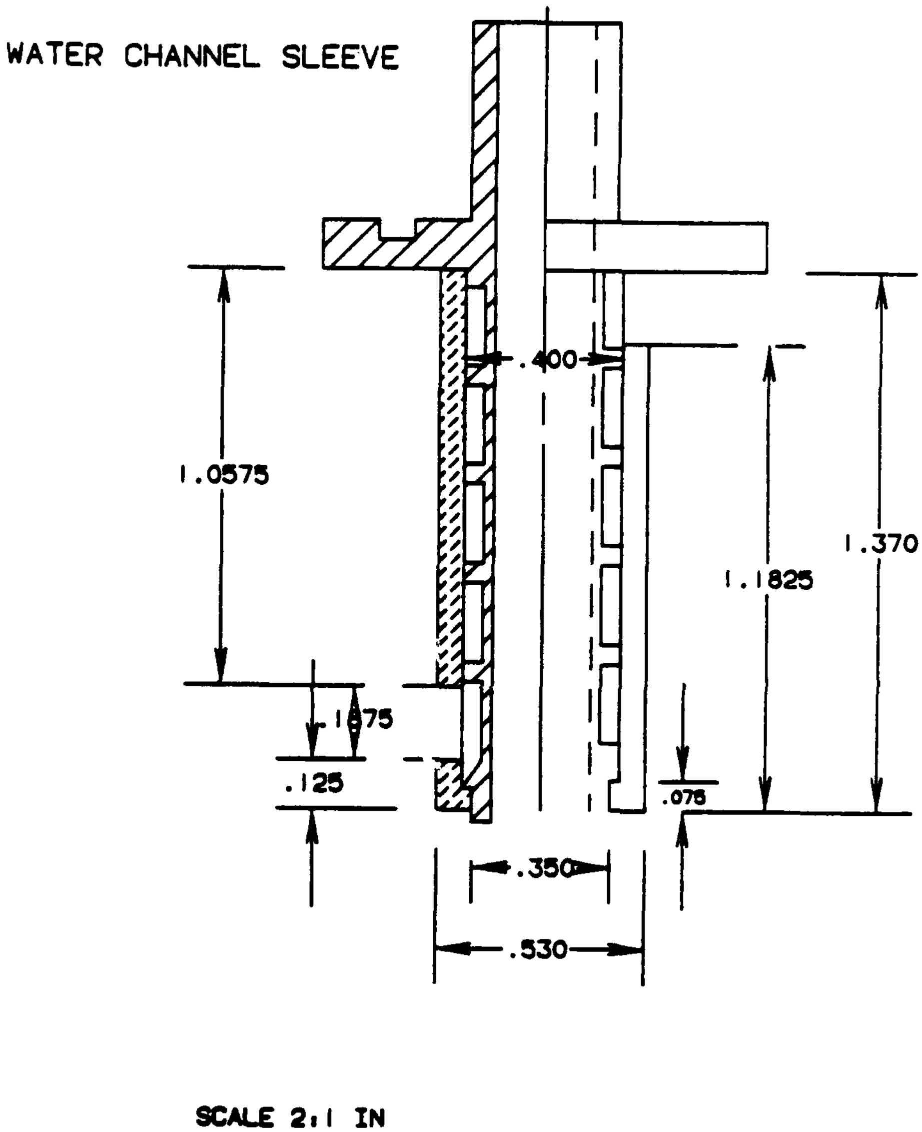


Figure 15. Water Channel Sleeve

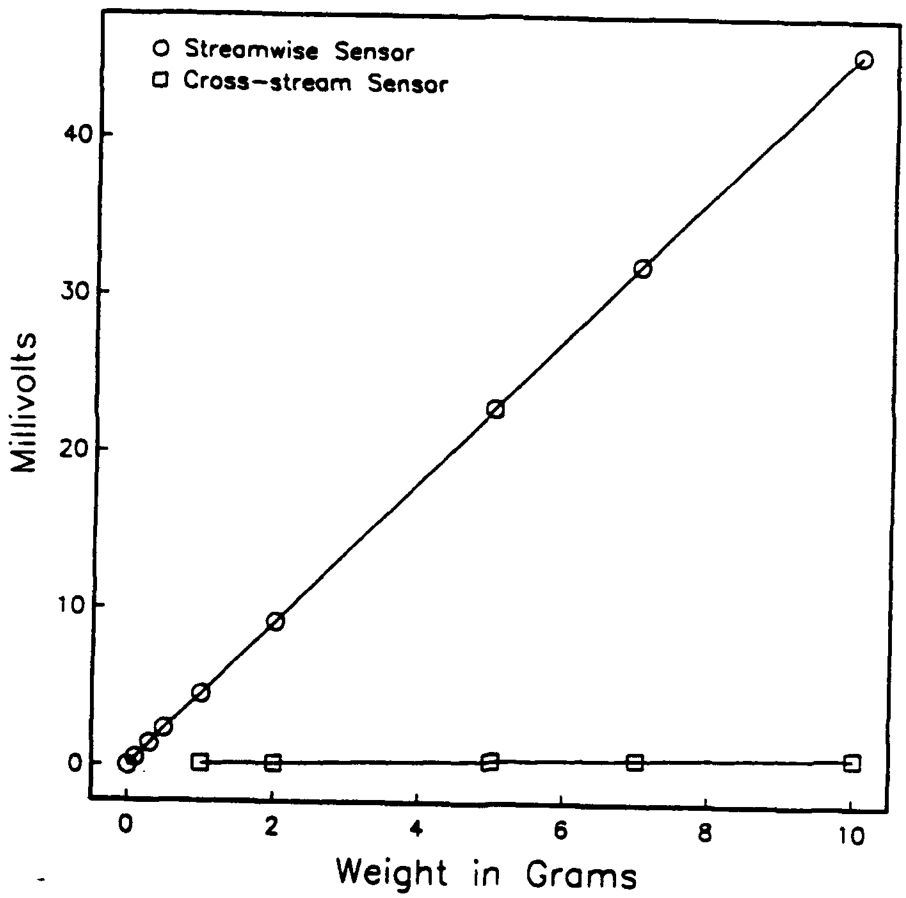


Figure 16. Skin Friction Calibration Curves

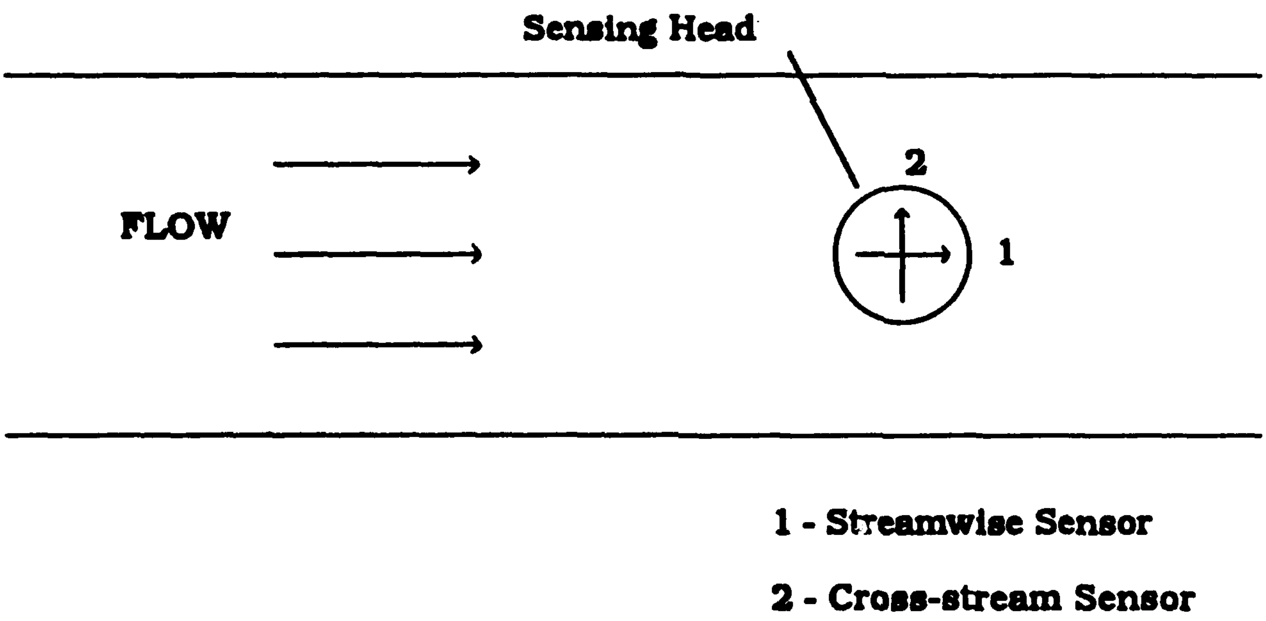


Figure 17. Orientation Of Sensor Axes

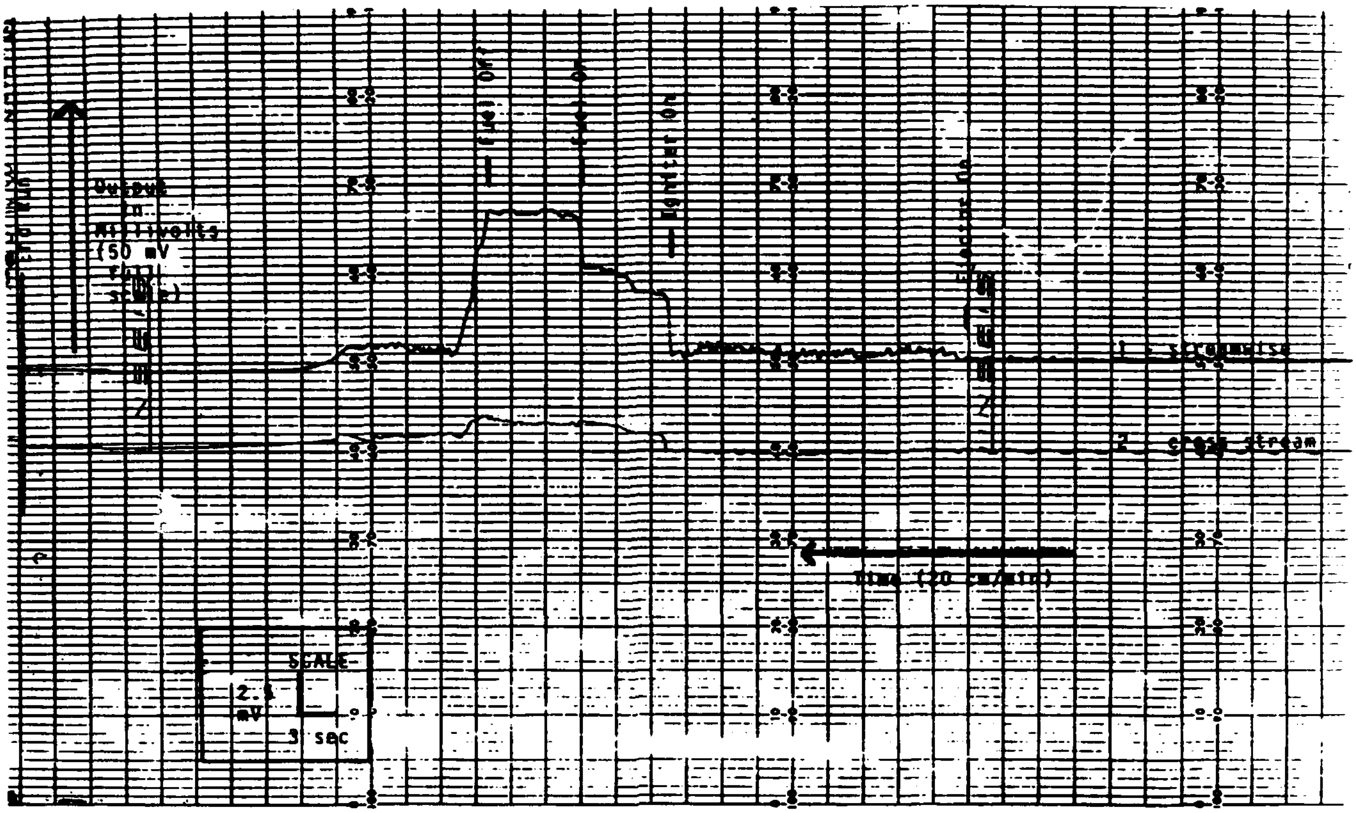


Figure 18. Skin Friction Gauge Output (Run 1)

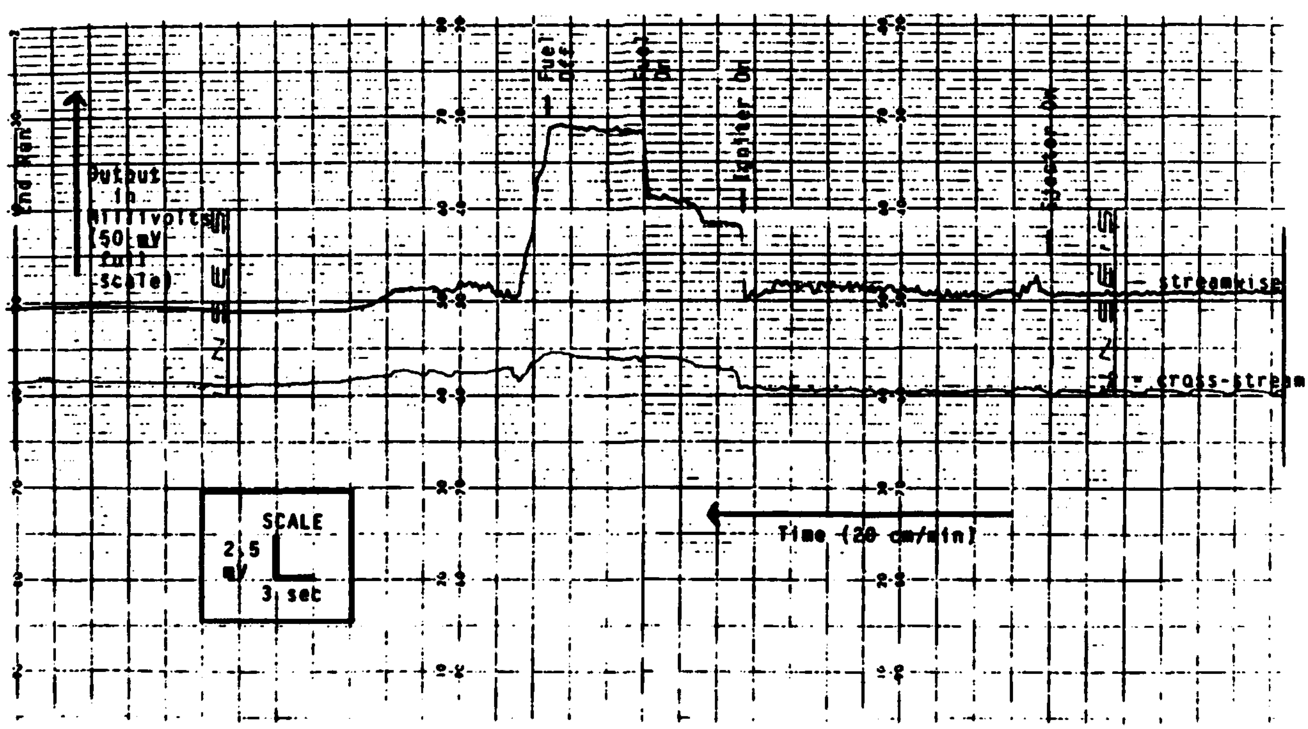


Figure 19. Skin Friction Gauge Output (Run 2)

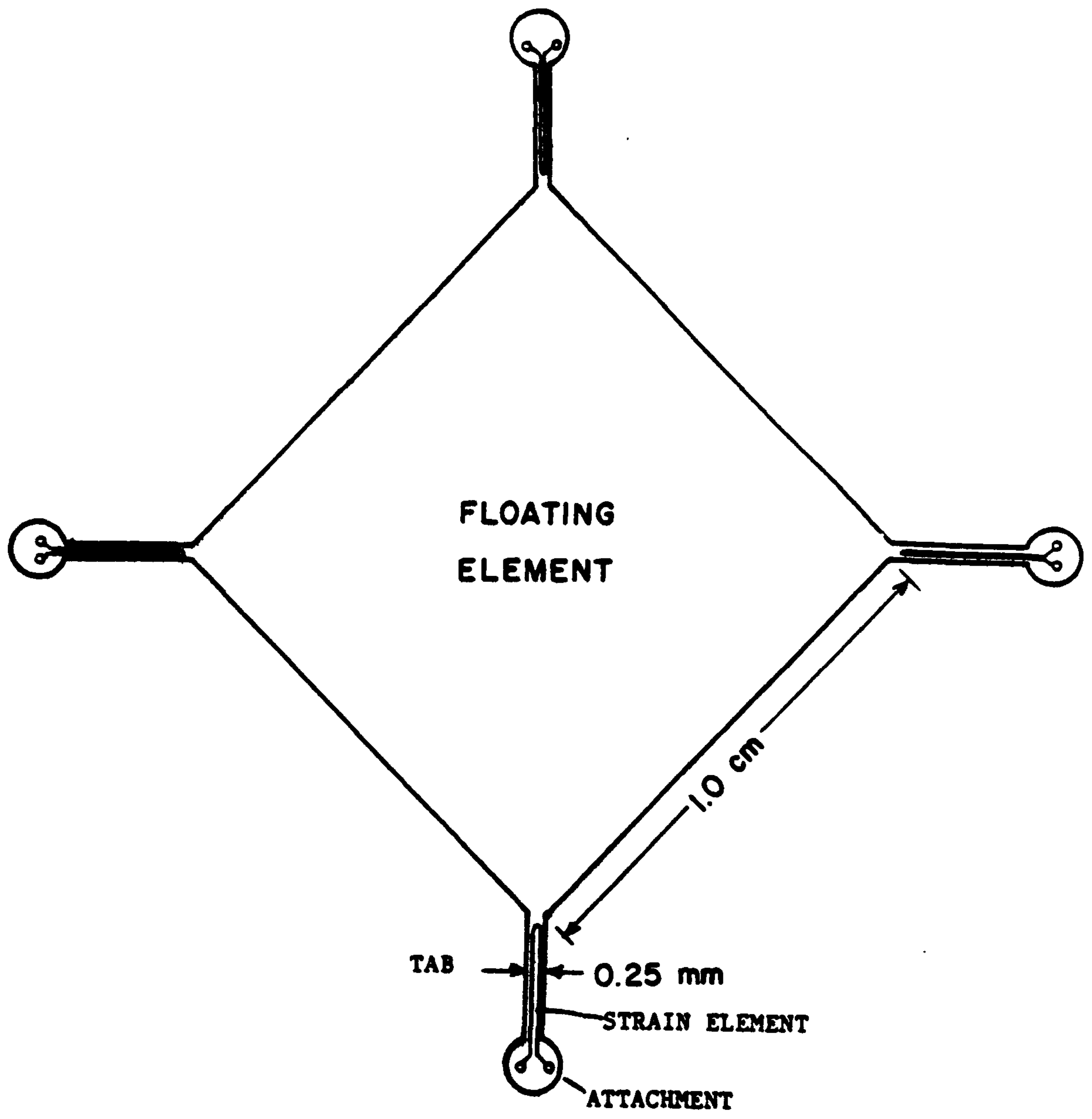


Figure 20. Design B - Thin Film Gauge

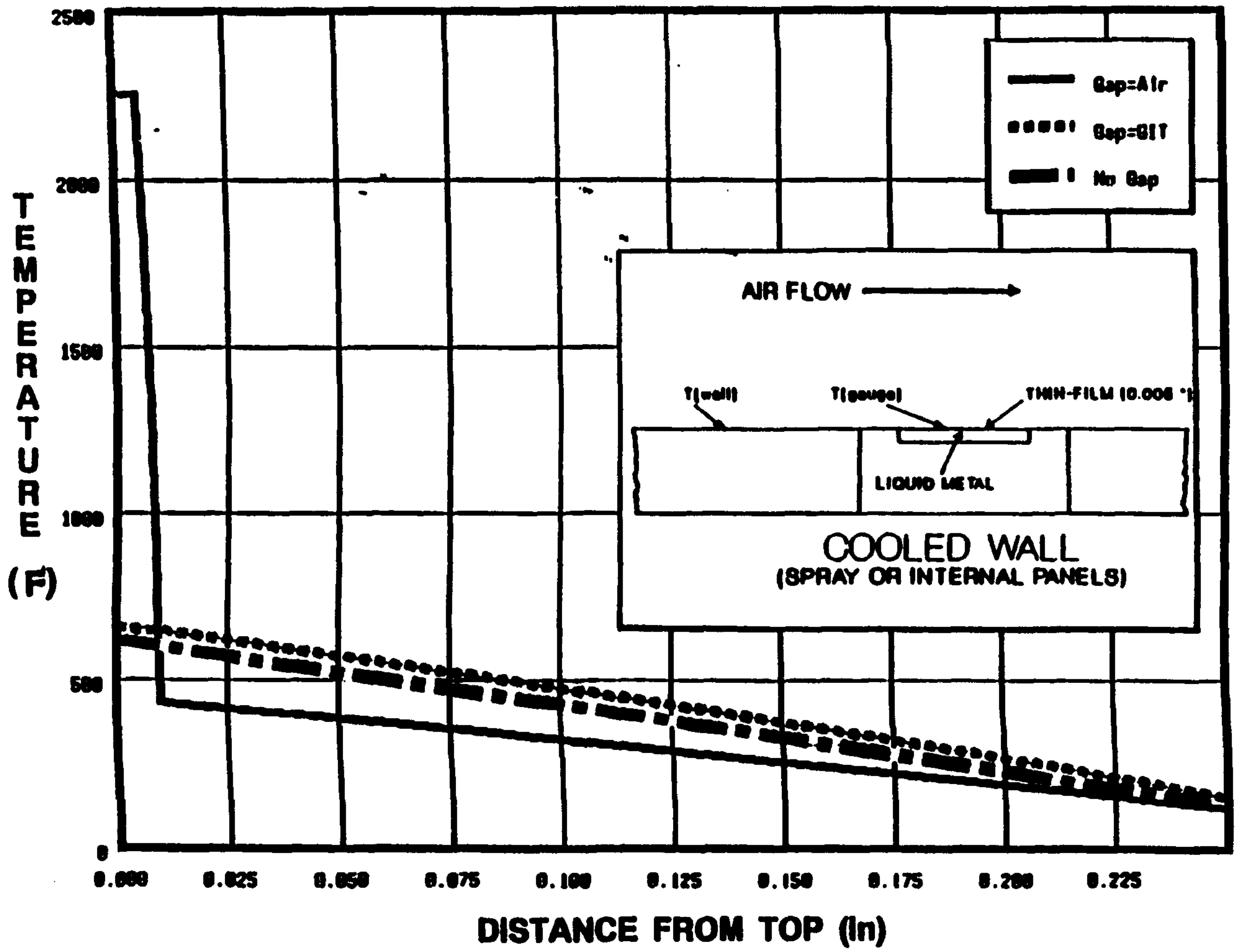


Figure 21. Comparison Of Air And GIT In The Gap

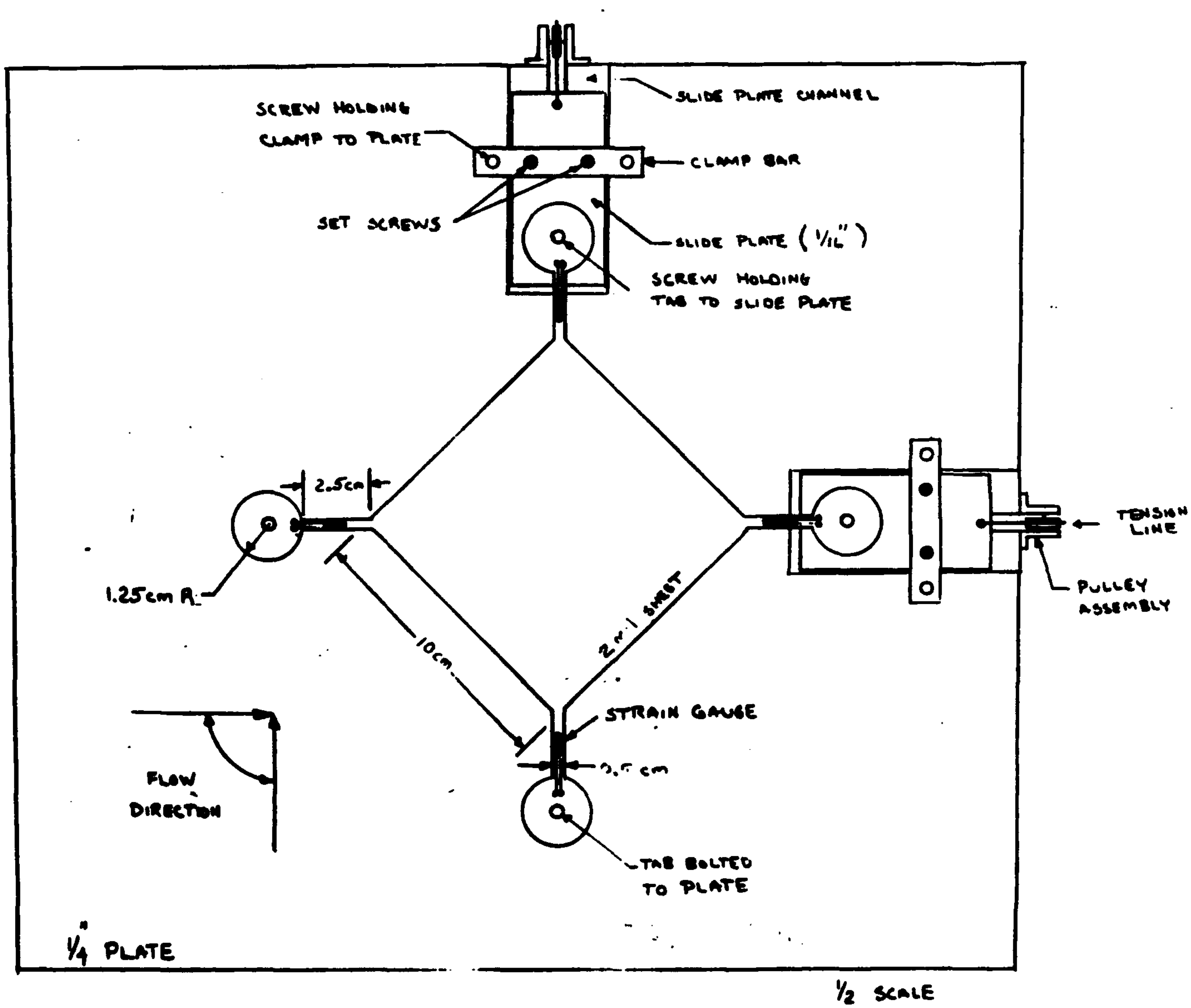


Figure 22. Test Rig For Thin Film Prototype

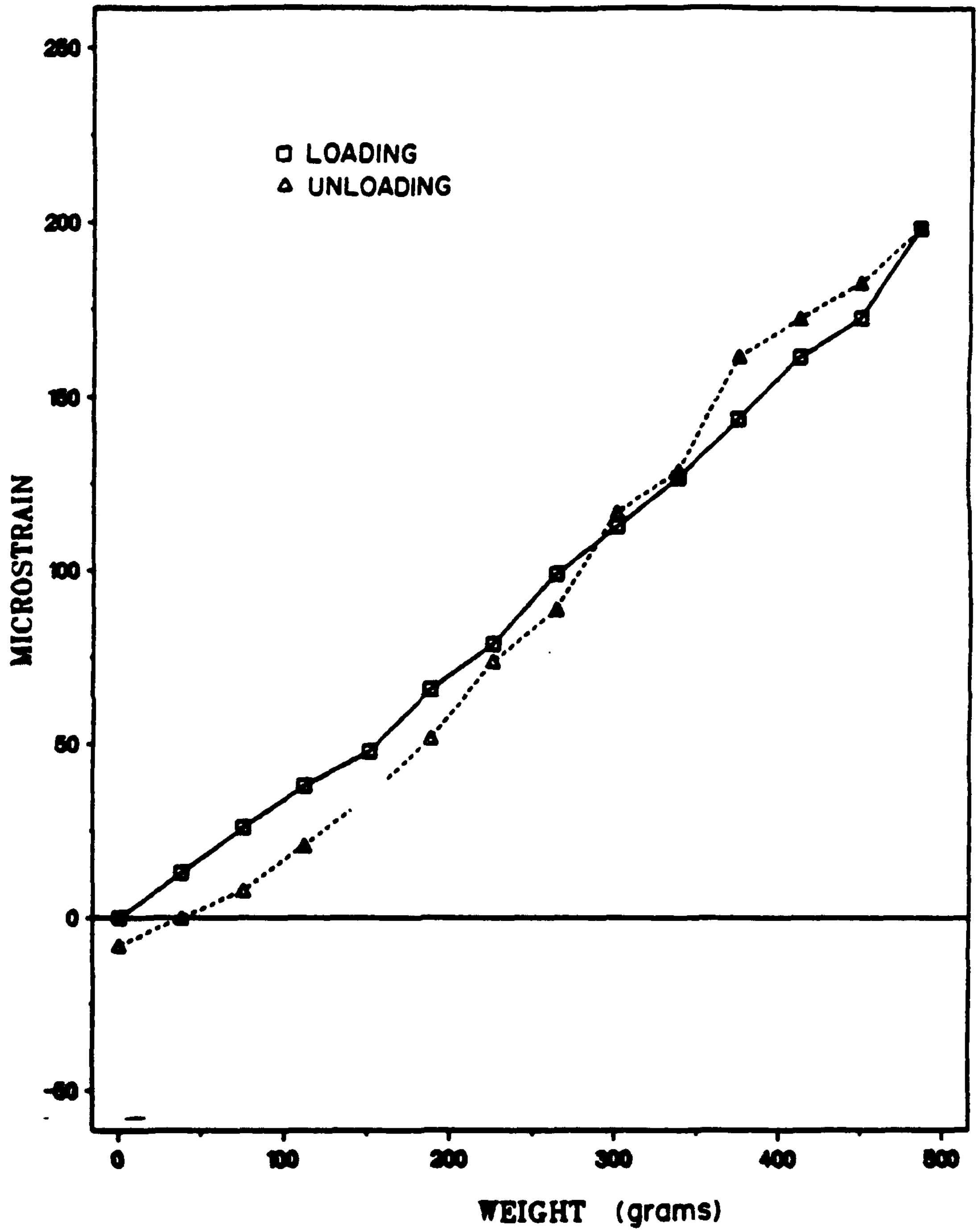


Figure 23. Static Calibration Of Thin Film Prototype

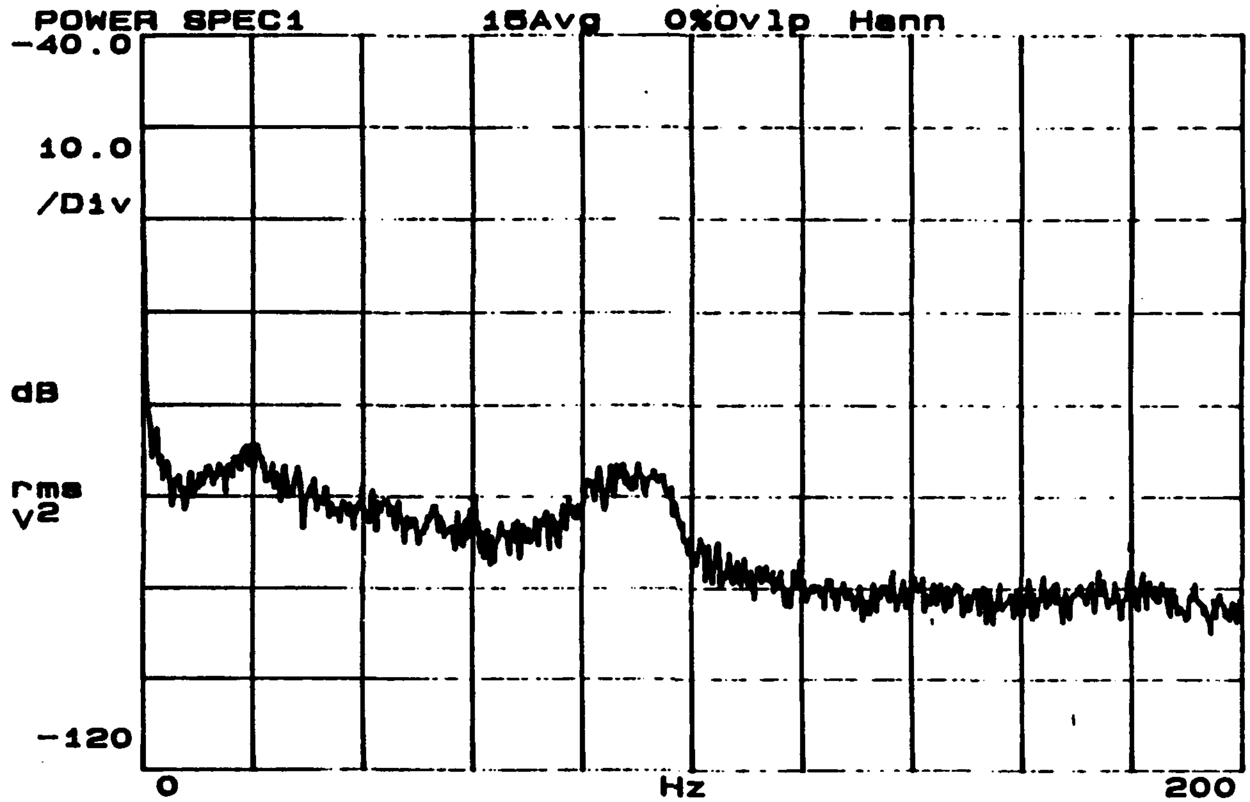


Figure 24. Vortex Shedding Measurements With Thin Film Prototype

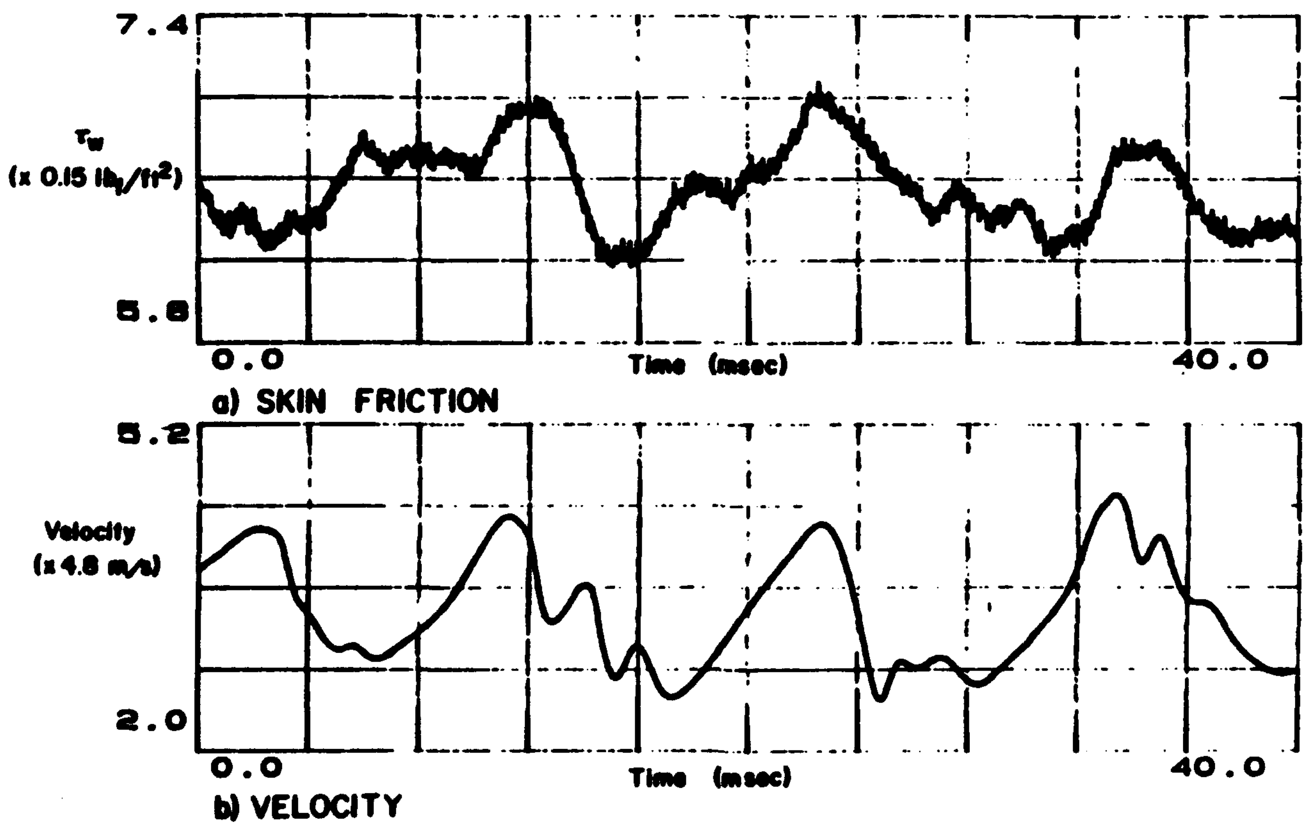


Figure 25. Unsteady Skin Friction Comparison With Hot Wire Anemometer

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